X6.9-class Flare Induced Vertical Kink Oscillations in a Large-Scale Plasma Curtain as Observed by SDO/AIA

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Received ________________; accepted ________________

For The Astrophysical Journal
ABSTRACT

We present rare observational evidence of vertical kink oscillations in a laminar and diffused large-scale plasma curtain as observed by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). The X6.9 class flare in the Active Region 11263 on 09 August 2011, induces a global large-scale disturbance that propagates in a narrow lane above the plasma curtain and creates a low density region that appears as a dimming in the observational image data. This large-scale propagating disturbance acts as a non-periodic driver that interacts asymmetrically and obliquely with the top of the plasma curtain, and triggers the observed oscillations. In the deeper layers of the curtain, we find evidence of vertical kink oscillations with two periods (795 s and 530 s). On the magnetic surface of the curtain where the density is inhomogeneous due to the coronal dimming, non-decaying vertical oscillations are also observed (period $\approx$ 763-896 s). We infer that the global large-scale disturbance triggers vertical kink oscillations in the deeper layers as well as on the surface of the large-scale plasma curtain. The properties of the excited waves strongly depend on the local plasma and magnetic field conditions.

Subject headings: Sun: corona – magnetohydrodynamics (MHD) – magnetic reconnection – Sun: flares
1. Introduction

The major concern of this paper is to understand the conditions for the excitation of vertical kink oscillations in a diffused and large-scale laminar plasma curtain. Kink MHD waves are exceptional in the sense that they are the only waves that displace the axis of a magnetic tube and the tube as a whole. For that reason the standing transverse MHD waves observed in coronal loops are interpreted as standing MHD kink waves. Apart from the transverse kink waves, there are claims that torsional Alfvén waves have been detected in various magnetic structures at diverse spatial scales in the solar atmosphere (e.g., Erdélyi & Taroyan 2007; Jess et al. 2009; and references cited therein). The observed Alfvén waves are potential candidates for heating the solar corona locally as well as for pursuing MHD seismology of the localized atmosphere (Harrison et al. 2002; Dwivedi & Srivastava 2006; Jess et al. 2009; Morton et al. 2011; DeMoortel & Nakariakov, 2012; Mathioudakis et al. 2013, and references cited there).

Horizontal kink oscillations triggered by flares have been observed in imaging observations of solar loops since the era of the Transition Region and Coronal Explorer (TRACE) followed by Hinode, Solar Terrestrial Relationship Observatory (STEREO), as well as Solar Dynamics Observatory (SDO) (e.g. Aschwanden et al. 1999; Nakariakov et al. 1999; Van Doorsselaere et al. 2008; Verwichte et al. 2009; Aschwanden & Schrijver 2011, Srivastava et al. 2013, and references cited there). Spectroscopic observations of kink waves are also reported for flaring and non-flaring active region loops (O’Shea et al. 2007; Erdélyi & Taroyan 2008, Van Doorsselaere et al. 2008, Andries et al. 2009) using respectively the Coronal Diagnostics Spectrometer (CDS)/SoHO and the EUV Imaging Spectrometer (EIS)/Hinode. Observations of kink waves are used to obtain estimates of plasma properties and of local physical conditions of the solar corona (Nakariakov & Ofman 2001; Goossens et al. 2002a; Andries et al. 2005a,b, Arregui et al. 2007; Goossens et al. 2008; Andries et
al. 2009). These weakly compressible kink waves are also observed in the stellar corona of the ξ-Boo (Pandey & Srivastava 2009, Anfinogentov et al. 2013).

Vertical kink waves have been detected in the solar atmosphere since the mid-2000, but only a few cases are known so far (e.g., Wang & Solanki 2004; Li & Gan, 2006; Aschwanden & Schrijver 2011; White et al., 2012, and references cited there). White et al. (2012) recently reported flare-induced vertical kink oscillations in an eruptive loop in the vicinity of a vertical current sheet. The off-limb coronal loop observed by White et al. (2012) is very symmetric and elliptical, and the flare disturbances that triggered the vertical kink wave occurred just below the apex of the loop somewhere near the limb. Selwa et al. (2011) claim that the excitation of vertical kink oscillations depends on the symmetry of the loop with respect to its interaction with the localized periodic drivers. They argue that the absence of symmetry prevents vertical kink modes while horizontal kink oscillations can be excited. Selwa et al. (2011) used this argument to explain why vertical kink oscillation are so rarely observed in the solar corona. Aschwanden & Schrijver (2011) have found that vertical kink oscillations can be triggered by flare-generated fast MHD waves. The propagation and interaction of large-scale coronal waves as well as coronal mass ejections (CMEs) can also trigger kink oscillations in the solar loops (e.g., Liu et al. 2011, 2012; Wang et al. 2012). Several theoretical and numerical investigations have tried to understand the vertical and horizontal polarized kink oscillations of coronal loops in the MHD regime (e.g., Gruszecki et al. 2006; Selwa et al. 2007; Mc Laughlin & Ofman 2008; Selwa & Ofman 2010, and references cited there). The onset of the appropriate triggering mechanism and physical conditions to excite the vertical kink oscillations are rare in the solar corona (Selwa et al. 2011; White et al. 2012). Therefore, there are only few observational reports in the context of the evolution of vertical kink oscillations in the solar atmosphere. However, sometime limitations in the observational base-line may make the identification of these vertical kink oscillations difficult as they might appear as horizontal kink oscillations due to projection
Horizontal and vertical kink oscillations can be a useful tool for constraining important properties of the localized corona (e.g., magnetic field) using MHD seismology (Nakariakov & Ofman, 2001; Arregui et al. 2007; Van Doorsselaere et al., 2008). The damping/growth of these waves may also provide clues about the role of dynamic plasma ambient (Ruderman 2011). MHD seismology based on the observations of multiple harmonics of kink waves, can lead to estimates of longitudinal density stratification (Andries et al. 2005a,b) and to longitudinal variation and expansion of the magnetic field (see e.g., Andries et al., 2009, and references cited there). Resonant absorption may be one of the potential mechanisms that can explain the observed fast damping of transverse standing and propagating kink waves. The transfer of energy from the transverse motions to the azimuthal Alfvénic motions is essential for the damping by resonant absorption (see e.g., Hollweg and Yang, 1988; Goossens et al. 1992; Ruderman and Roberts, 2002, Goossens et al., 2000b, 2006, 2009, 2011, 2012). The transverse kink motions may undergo rapid dissipationless damping because their energy is transferred to the azimuthal Alfvénic motions. The eventual damping of the azimuthal Alfvénic motions is not dissipationless and probably much slower than the dissipationless damping of the transverse motions. This mechanism of dissipationless damping is universal in the sense that it works for both standing and propagating waves (see e.g., Terradas et al. 2010, Verth et al. 2010, Pascoe et al. 2010, 2012). A concern about resonant absorption as a dissipationless damping mechanism of transverse (horizontal or vertical) kink waves is the lack of the observation of the azimuthal Alfvénic motions in the vicinity of the resonant position. Other potential mechanisms for the damping of the transverse waves may be phase-mixing (Ofman & Davila 1995; Nakariakov et al. 1997), dissipation of kink and Alfvén waves waves by small-scale turbulence (Nakariakov et al. 1999; Van Ballegooijen et al. 2011), and even the simple relaxation of the active region field lines. Therefore, study of the damping and dissipation of differently polarized transverse
kink oscillations in the magnetized solar atmosphere is of significant importance in the context of the coronal heating.

In the present paper, we outline the rare observational evidence of kink vertical transverse oscillation in different parts of a large-scale laminar plasma curtain formed by diffused and unresolved thin loop threads in the off-limb corona of the western equator. This is the first detection of collective vertical transverse oscillations in a large-scale plasma curtain. The large-scale plasma curtain is very different from individual coronal loop strands for which MHD seismology was originally devised. The classic version of MHD seismology almost invariably uses the thin-tube or short wavelength approximation in cylindrical waveguides (Roberts 1981, Aschwanden 2004) (cf., review by Andries et al. 2009 and references cited there). The detection of vertical oscillations in the present large-scale plasma curtain may require new modeling attempts beyond the existing theoretical approach for tubular waves and MHD seismology (Roberts 1981; Nakariakov & Verwichte 2005). Indeed the spatial dimensions of this large scale laminar plasma curtain are very long and the inhomogeneity length scales of plasma and magnetic field properties are also far longer than those considered in the presently existing tube-wave theories (Roberts, 1981; Nakariakov & Verwichte 2005). The present paper aims to discuss the detection, possible excitation as well as dissipation of the vertical kink oscillations seen in the plasma curtain. The X6.9 flare blast loci on 09 August 2011, situated in the northward direction on the solar disk, generate global disturbances that interact with this magnetized plasma medium asymmetrically and obliquely. These global disturbances most likely excite vertical kink oscillations in the deeper layer as well as at the outer interface of the plasma curtain. The rest of the paper is structured as follows. In section 2 we describe the observations. In section 3 we report the detection of vertical kink oscillations and their implications in the observational base-line of Atmospheric Imaging Assembly (AIA) onboard Solar Dynamics Observatory (SDO). In section 4 we offer a theoretical interpretation of the observed
oscillations. The last section is a summary and discussions on the major findings of our paper.

2. Observations

A X6.9 class solar flare was observed in the active region AR11263 (N17 W69) near the western equatorial limb on 09 August 2011. The flare started at 07:48 UT with a peak intensity at 08:05 UT. The flare ended at 08:08 UT and is classified as an impulsive event. In the present paper we have used imaging data showing the flare induced oscillatory dynamics of a laminar plasma curtain formed by unresolved, diffused and thin loop threads as observed by the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO). The large-scale plasma curtain was situated in the off-limb corona at the western equator in the southward direction of the flaring active region (cf., Fig. 1). AIA has a maximum resolution of 0.6 per pixel and a cadence of 12 s. AIA provides full disk observations of the Sun in three ultra-violet (UV) continua at 1600 Å, 1700 Å, 4500 Å, and seven Extreme Ultraviolet (EUV) narrow bands at 171 Å, 193 Å, 211 Å, 94 Å, 304 Å, 335 Å, and 131 Å, respectively (Lemen et al. 2012). Therefore, it provides observations of multi-temperature, high spatial and temporal resolution plasma dynamics in the solar atmosphere. For the current analysis of the flare-induced oscillations of the diffused plasma curtain, we have used the data recorded by AIA 171 Å filter. The image sequence recorded in 171 Å ($T_f \sim 10^6$ K) reveal information about the inner coronal plasma. The flare generated global disturbances and these global disturbances in turn triggered the observed vertical transverse oscillations. We use the SDO/AIA data to capture the signature of these rare oscillations in the large-scale plasma structure in the solar corona because of the unique position of the magneto-plasma structure almost perpendicular to the line-of-sight (LOS). To constrain the morphological evolution of large-scale disturbances
and creation of the narrow dimming lane above the plasma curtain, we use temporal image data in form of the difference images of 171 Å (cf., Fig. 2). The time-series of SDO/AIA data has been reduced by the SSW cutout service.

3. Detection of Vertical Kink Oscillations in the Large-Scale Laminar Plasma Curtain by SDO/AIA

Fig. 1 shows the images of the active region AR 11263 and its surrounding areas on 09 August 2011. SDO/AIA 171 Å (left) on 08:07 UT and its difference image (right) show (i) the X6.9 flaring region, (ii) the diffused and laminar plasma curtain formed by the unresolved thin loop threads, (iii) a narrow off-limb lane of the propagation of flare generated disturbances above the curtain, and (iv) on-disk large-scale global disturbances, respectively by red, blue, green, yellow arrows. The difference image of AIA 171 Å on 08:07 with the image of the same FOV on 07:50 UT shows clearly a dimming in the form of an EUV coronal wave after the maximum onset and energy release of the X6.9 flare. The wavefront propagates as a global disturbance in the on-disk part in South-East of the flaring region. However, the wave disturbance does not pass through the plasma curtain directly, and some part of the disturbance only propagates through the narrow lane above the plasma curtain. For comparison, we display the STEREO-A, EUVI 195 Å image at 08:10 UT on 09 August 2011 (Fig.1 bottom-panel; Wuelser et al. 2004). The AR 11263 with its X-class flare energy release lies near the centre in the North-East quadrant of the Sun. It is clearly evident that the core off-limb loops in the western side of the flaring region partly visible in SDO/AIA field-of-view, are large-scale diffused loops adjoining the two active regions as shown by black arrow. However, the large-scale diffused plasma curtain

http://lmsal.com/get_aia_data/
that lies more to north-southward is not visible in the STEREO-A. This may be due to its lower density and emissions in the on-disk view of STEREO-A EUVI 195 Å snapshot. In the SDO/AIA field-of-view (FOV), the same plasma curtain is visible off the limb, and lies almost perpendicular to the meridional plane and to our line-of-sight (LOS). This comparison is to show that the plasma curtain is very different from normal loop systems as it is very diffused at long spatial-scale and has a low density contrast compared to the ambient atmosphere that made it invisible on solar disk.

Fig. 2 shows the time sequence of the difference images in AIA 171 Å channel to examine the evolution of the large-scale global disturbances and formation of narrow-dimmed lane at the top of plasma curtain. After the flare peak energy release at 08:05 UT, the on-disk part of the global EIT wave moves as an almost semi-circular wavefront in the South-East direction with a speed of \( \approx 750 \text{ km s}^{-1} \). However, it does not propagate in the form of a symmetric wavefront in the direction of the plasma curtain as observed under the base-line of SDO/AIA observations. Nevertheless, a narrow dimming region is formed above the plasma curtain that allows the fast moving disturbance to propagate above the surface of the plasma curtain (see snapshot on 08:10 UT). This disturbance pushes the curtain from the upward side to the downward direction, and the vertical transverse oscillations start after 08:10 UT onwards in the certain part of the plasma curtain (cf., VTO-SDO.mpeg). It should be noted that the triggered oscillations are perpendicular to the LOS almost along the equatorial plane, and thus polarized in form of vertical transverse oscillations. It should also be noted that the western core loops connecting the two active regions are visible in STEREO-A field-of-view, however, more southwardly stretched plasma curtain and higher parts as visible in SDO/AIA of this diffused magnetic structure is unfortunately not visible in STEREO-A most probably due to the less density and emissions. Therefore, we only estimate the oscillatory properties of the fully visible plasma curtain in SDO/AIA. Moreover, the unique position of the plasma curtain in SDO/AIA field-of-view provides us
an opportunity to detect these oscillations in the deeper layers as well as at the surface of the plasma curtain. Therefore, to measure and compare the oscillation properties of the deeper as well as the surface layers of the plasma curtain, we only use the observations of SDO/AIA 171 Å filter data. Let us now investigate the properties of flare generated vertical transverse oscillations in the large-scale plasma curtain as observed by SDO/AIA.

In Fig. 3, we display the Distance-Time diagram (bottom-left) along a vertical slit (top-left) that is placed vertically over the plasma curtain in the northward side nearer to the flare blast region. The vertical transverse kink oscillations occur in the deeper layer of the curtain, while the surface of the curtain does not show clear oscillatory signature in a similar way. The Distance-Time (bottom-middle) along a parallel vertical slit (top-middle) placed at the middle of the curtain shows vertical oscillations in its deeply rooted almost same layer, as well as vertical oscillations of its surface. The Distance-Time (bottom-right) along a parallel vertical slit (top-right) placed in southward region on the opposite side of the curtain near to the flaring region shows oscillations that are only clearly visible at the surface, but that appear to be smoothed out from the deeper layers. We also examined the distance-time map along the path traced out perpendicular to the plasma curtain and parallel to the polar axis (not shown here). We did not find any signature of propagating kink wave trains along the length of the plasma curtain at larger spatial scales at its various heights. This means that only localized vertical kink oscillations are triggered in various parts of the plasma curtain as shown in Figure 3.

In Figs. 4-5, we display the power spectrum analysis of these oscillations carried out using standard wavelet technique (Torrence & Compo, 1998) and randomization method (Linell Nemec & Nemec 1985, O'Shea et al., 2001). Let us firstly look at the vertical oscillations that occur in the deeper layer, which is 30-40 Mm below from the dome-shaped curvilinear outer surface of the plasma curtain. The two panels of Fig. 4 show the
oscillations at two different spatial parts of the same deeper plasma layer, which is most likely formed by a bunch of denser and unresolved loop threads (cf., vertical oscillations of the same deeper layer in bottom-left and bottom-middle panels of Fig. 3). In the first spatial part that lies northward in this layer of the plasma curtain and is closer to the flare blast site, we find vertical oscillations with a period of $\sim 530$ s and a maximum amplitude of about $\pm 4.0$ Mm. In the second spatial part that lies southward in this layer of the plasma curtain away from the flare blast site in its middle, we find vertical oscillations with a period of $\sim 795$ s and a maximum amplitude of about 5.0 Mm. Let us now turn to the outer curvilinear surface of the plasma curtain. This acts as magnetic interface between the magnetized and denser plasma curtain and the outer approximately field-free and less dense region. Initially it does not exhibit clear oscillatory motion in its northward part. However, the oscillations are clearly observed near its middle as well as in the southward off-side from the flare blast region. The observed periods of these oscillations are between 764-896 s with maximum amplitudes of $\pm 5.0-6.0$ Mm (cf., Fig. 5). It should be noted that significant oscillatory power is only evident in all these measurements in the intensity wavelet, when the transverse oscillations are switched-on. The transverse oscillations are not confined to a single thin flux-tube, but they rather evolve over several layers of the laminar plasma curtain.

4. Interpretation

We interpret the observed oscillations in the deeper layer of the plasma curtain as vertical kink oscillations. The oscillation with a period of 795 s might be the fundamental kink oscillation. The reason for this suggestion is that in most cases known so far it is the fundamental mode that is excited during a flare energy release. The period of the fundamental mode seems to be rather long compared to the previously detected periods in
isolated coronal loops. However, it should be noted that the oscillating part in the middle of the plasma curtain is very long \((L \sim 530 \text{ Mm})\), and the phase speed of the fast mode kink wave \((c_k)\) is \(2L/P \sim 1332 \text{ km s}^{-1}\). The plasma curtain has very low density contrast \((\rho_e/\rho_o \sim 1.0)\) compared to the background coronal plasma as it is invisible in the on-disk view in STEREO image (cf., Figure 1). Therefore, the observed kink speed \((c_k)\) of \(\sim 1332 \text{ km s}^{-1}\) is almost equal to the internal localized Alfvén speed of the plasma curtain \(C_{A_o}\). This Alfvén speed is comparable to the typical inner coronal Alfvén speed of 1000 km s\(^{-1}\). In the same frame of mind the oscillation with a period of 530 s could be interpreted as the first longitudinal overtone. The period ratio is clearly smaller than 2.0 but that might be caused by stratification of density along the magnetic field (Andries et al., 2005a; Andries et al. 2005b, Andries et al., 2009; and references cited there). The fundamental and first overtone are obvious candidates, but we have no hard evidence to claim that the observed oscillations indeed correspond to these modes. If we consider these two vertical kink oscillations as the first two longitudinal harmonics then the ratio of the periods can be used to estimate the density scale height as in Andries et al. (2005a). Here we use the approximation derived by McEwan et al. (2008) for the variation of \(P_1/2P_2\) as a function of the ratio of half loop length \((L/2)\) and \(\Lambda_c\) to obtain an estimate for the scale height in the middle part of the plasma curtain where these two oscillations are generated. The length \(L\) of this layer along its curved path between two opposite ends is approximately 530 Mm in the projection of the plane. Therefore, the scale height is estimated as \(\Lambda_c \sim 88 \text{ Mm}\). The scale height is very close to the typical hydrostatic scale-height of the inner corona at 1.0 MK temperature, i.e., \(\sim 80 \text{ Mm}\), when we take into account the uncertainty on the estimate of the length of the oscillating part in the middle of plasma curtain. Therefore, we conjecture that this very large plasma curtain is in the hydrostatic equilibrium conditions. This also favours the fact that at the longer spatial scales, the corona can be considered and modelled as a system in the hydrostatic equilibrium. However, deviations from hydrostatic equilibrium are likely
to occur in local coronal structures with shorter spatial scales in form of the flux-tubes, e.g., isolated loops, coronal X-ray bright points etc (e.g., McEwan et al. 2006, 2008; Andries et al. 2009; Srivastava & Dwivedi 2010; Kumar et al. 2011; Luna-Cardizo et al. 2012, and references cited there). The amplitudes initially increase in time and subsequently the oscillations all of a sudden vanish from different spatial positions in the same deeper layer of the plasma curtain. This behaviour and dissipative nature are similar to the well-known fast damping for horizontal transversal standing waves of the coronal loops (Aschwanden et al., 1999; Nakariakov et al., 1999). In the typical solar atmosphere for $\mu=0.6$ and $\gamma=1.67$, the magnetic Reynold number can be approximated as $R_m = 1.9 \times 10^{-8}V_oT_o^{3/2}/\ln\Lambda$ (Priest, 1982). For the portion of the observed plasma curtain that as a whole undergoes vertical kink oscillations, the length scale, Alfvén velocity, typical temperature for the formation of Fe IX emission are respectively 530 Mm, 1332 km s$^{-1}$, and 1.0 MK. For the typical inner coronal density of $10^9$ cm$^{-3}$ and temperature of 1.0 MK, the columb logarithm (log\Lambda) is $\sim 19.3$ (Priest 1982). Therefore the magnetic Reynold number $R_m$ is very high for the observed plasma curtain, which is $\sim 7.0 \times 10^{14}$. This is seven order of the magnitude higher than the Reynold number of the environment above a typical photospheric spot, i.e., the coronal loop plasma medium (Priest 1982). This clearly indicates that the collective motion of the plasma is tightly coupled with the magnetic field lines over the length-scale of the observed plasma curtain. Therefore, the numerical modelling of the kink oscillations in such plasma curtains need the very high magnetic Reynold number environment.

The rapid disappearance of the excited vertical kink oscillations might also be due to a change of angle between the line-of-sight and the plane of the polarization. However, actual damping mechanisms may cause the oscillations to disappear. We will discuss the most plausible candidates for damping and dissipation in the forthcoming sections.

Another possibility is the detection of two independent kink vertical oscillations in
two different parts of the same deeper layer of the plasma curtain. The origin of these independent vertical kink oscillations can depend on the energy of the driver, the nature of the interaction with the localized portion of the curtain having specific plasma and magnetic field properties. It is clear that the northward deeper layer, which is near to the flare energy release site, supports comparatively high frequency (low period; 530 s) vertical oscillations. This is the location that may serve as the interaction region with a more energetic global wavefront that originated near the flare blast locus. When we examine the same deeper layer situated southward from the flare blast locus, we find vertical oscillations with comparatively low frequency (or long period; 796 s). This is the location that may serve as the interaction region with a comparatively less energetic front of the global disturbance that already lost part of its energy on its way in the solar corona. In the far-southward situated region of the same deeper layer of the curtain, collective vertical oscillations cannot be clearly identified. This region is the remotely positioned interaction region where the global disturbance fails to pump sufficient energy to trigger oscillations.

We conjecture that the global disturbance transfers its energy locally to different parts of the plasma curtain depending upon the local plasma and magnetic field conditions there. Hence, the global disturbance excites different vertical oscillatory modes in different regions (Ballai et al., 2005). The study of this interaction is outside of the scope of this paper.

These alternative interpretations also seem likely as we could not get any evidence of running kink wave trains across the major axis of the large-scale curtain drawn parallel to the solar North-South axis as well as meridian plane. We only have evidence of localized vertical oscillations in various parts of the curtain as shown in Fig. 3.

We do not aim here to model the presently observed large-scale system where the oscillations are excited. But we would like to point out what we understand with the term "Laminar Plasma Curtain" system. It cannot be viewed as a single magneto-plasma system since that would violate the equilibrium conditions. On the contrary, as we stated in the
beginning, the system is made-up of many thin un-resolved semi-circular diffused loops and the plasma filling factor is at larger spatial scale than the width of a single average fluxtube. The whole structure resembles a large-scale curtain, and the word 'laminar' refers to this structuring in the form of unresolved fluxtubes. The observed kink motions are the collective antisymmetric transverse motions of magnetic field and associated plasma. However, these perturbations are distributed over a comparatively longer spatial scale, i.e., in more wide regions of the plasma curtain.

Let us focus on the excitation of the vertical transverse waves of the present investigation. The X6.9 class flare in the Active Region 11263 on 09 August 2011 induces a global large-scale disturbance that propagates in a narrow lane above the plasma curtain and creates a dimming region with lower density. This large-scale propagating disturbance acts as a non-periodic driver that interacts asymmetrically and obliquely with the plasma curtain, and triggers waves. This differs from the observations by White et al. (2012). White et al. (2012) observed vertical kink oscillations in a flaring loop, with a period of 5.0 min. They conjectured that the oscillation is driven by the periodic reconnection and formation of a post-flare hot loop on a scale of a 5.0 min periodicity, and is not due to flare-generated blast waves. Here we observe similar oscillations in a large-scale and diffused plasma curtain triggered by flare generated global disturbances. Moreover, the observed periods of 795 s and 530 s are quite long compared to the 5.0 min scale. Although, the curtain is formed by laminar arrangements of thin loop threads we unfortunately, can not resolve them in the present observational base-line. The oscillations are triggered unambiguously in that part of the curtain where the plasma layer is slightly denser. This observational situation should also be confronted with the numerical findings of Selwa et al. (2011). Selwa et al. (2011) theorized that the amplitude of vertical kink oscillations in a dipolar coronal loop is significantly amplified in comparison to that of horizontal kink oscillations for a pulse driver that is located symmetrically below the loop. In inclined
loops they could not identify vertical kink oscillations. They used this scenario to explain the scarcity of vertical kink oscillations in the corona. Our observations of vertical kink oscillations show a scenario that is completely different from their findings since here the vertical kink oscillations are excited by a non-periodic and non-symmetric driver, i.e., flare generated global coronal waves.

Let us now turn to the observations of oscillations on the surface of the plasma curtain. There we also observe a vertical kink oscillation, now with a period between 763 and 896 s. This oscillation is uniformly distributed near the middle and southward side of the plasma curtain surface. However, it appears to be absent from the surface of the plasma curtain in the northward side that is nearer to the flare site. The amplitude of this oscillation does not show any signature of decay in the present available observational baseline.

The curtain lies almost in the part of the equator near the west-limb, so that the density can be taken to be a smooth function of the radial outward distance inside it. In the deeper layers of the plasma curtain the density is almost constant and the kink waves have predominantly vertical transverse motions. Above the northward surface of curtain, the dimming is comparatively weak (cf., snapshot 08:10 UT in Fig. 2) and the spatial changes in density are smaller inside and outside of the surface. The dimmed region is clearly present near the middle of the surface as well as at the surface in the southward direction. This implies a clear spatial change in density and local Alfvén speed at different spatial locations (northward, middle and southward) above the surface of the plasma curtain in the corona assuming that the background magnetic field is constant. This spatial variation of density and local Alfvén speed increases the relative importance of the azimuthal component of the displacement with respect to the radial component at different locations at the surface of plasma curtain. The vertical kink oscillations that grow at the surface of the plasma curtain during the coronal dimming, have velocity components perpendicular to our LOS.
These surface oscillations do not decay while the oscillations in the deeper layers decay in the observational base-line of SDO/AIA. The reason may be that the continuous dimming due to the passage of fast global disturbances above the curtain creates a low density region. A variation in density in the radial direction can cause damping of standing and propagating waves due to resonant absorption (cf., Goossens et al., 2000b, 2006, 2009, 2011, 2012; Terradas et al. 2010). Density variation along the loop can impede the damping due to resonant absorption or even cause amplification (Soler et al., 2011). Time dependent variation of the background density counteracts the damping due to resonant absorption of standing waves and even cause amplification (Ruderman, 2011). The cooling and variation of the background plasma properties may also cause the damping of the loop kink oscillations (Morton & Erdélyi 2009, 2010a, Morton et al. 2010b, and references cited there). However, this scenario is not in support for the present observations as we do not get any signature of cooling of the plasma curtain. Resonant absorption may cause a transfer of energy of the vertical oscillations in the deeper layers towards the outer surface and cause their dissipation. The density decrement above the surface due to dimming may counter-act this dissipation by resonant absorption and the oscillations may not be dissipated as observed by SDO/AIA. Similar conditions have been observed by Wang et al. (2012) as a coronal dimming above a loop due to CME caused the amplification of kink oscillations. In the present case, the surface oscillations are not amplified, but remain unchanged and do not undergo dissipation.

5. Summary

Let us recall the major concern of this paper is to understand conditions for the excitation of vertical kink waves in a large-scale and diffused plasma curtain. It is clear that the kink waves that are observed in the present study are excited by a large scale
propagating disturbance that acts as a non-periodic driver and interacts asymmetrically
and obliquely with the plasma curtain. This way of excitation differs from that active
in the observations by White et al. (2012) where the vertical kink waves are excited by
a periodic and symmetric driver. There is nothing wrong with vertical kink oscillations
excited in two different ways. However, our observations contradict the conjecture by Selwa
et al. (2011) that the excitation of vertical kink oscillations requires a driver that is located
symmetrically below the loop. Further numerical modeling is needed here keeping the
present observations in mind.

The major challenge opened by this first observational findings of vertical kink
oscillations in the large-scale plasma curtain, is to try and understand how these waves
can be excited in such systems beyond the thin tube approximation. If different vertical
oscillations in different spatial locations of the plasma curtain are generated by one-to-one
interactions with global wave energetic fronts, then the evolution of these waves and the
transfer of energy depend on the structure of magnetic field and the composition of the
medium in which the waves are generated and propagate. Hence MHD models of kink
waves in large-scale plasma structures as observed in our paper need to be developed.
The high magnetic Reynold number plasma environment of the curtain that is almost
maintained in hydrostatic equilibrium at larger spatial scale is set in the vertical kink mode
oscillations, which are non-decaying at the surface while quickly decaying on its deeper
layers. The non-decaying and decaying kink oscillations have been recently observed in
coronal loops that are driven respectively by the low amplitude continous and harmonic
driver, and high amplitude impulsive driver (Nisticò et al. 2013). They have reported that
impulsive excitation generates systematically the transverse perturbations in all the loops.
We also do observe the vertical oscillations over larger spatial scales that are generated by
the impulsive exciter, however, in our case both the decaying and decayless oscillations are
seen to be associated with the same impulsive driver. Therefore, the opposite nature of
the surface oscillations as well as the oscillations in the deeper layer of the plasma curtain, indicate about the creation of some resonant layers. It is also likely that the resonant absorption is at work in decaying the vertical oscillations of the deeper layers of curtain that are associated with the impulsive driver. However, the dimming above its surface most-likely counter act on it and keeping the surface oscillations un-damped. The detailed theoretical investigations of the excitation and dissipation of such vertical kink oscillations in the large-scale plasma curtain is the subject of our future work, and outside the scope of this paper.

In the present paper, in conclusion, we report a very likely physical scenario for the unique observations of the vertical transverse waves in a large-scale plasma curtain. However, more study should be made further using space borne observations and stringent modeling to shed new light on the physics of this coronal dynamics.

6. Acknowledgments

We thank referee for his valuable suggestions that improved the manuscript considerably. We acknowledge the use of the SDO/AIA observations for this study. The data are provided by the courtesy of NASA/SDO, LMSAL, and the AIA, EVE, and HMI science teams. AKS also thanks Shobhna Srivastava for her support and encouragement during this work. MG acknowledges support by the University of Leuven grant GOA/2009-009 and also partial support by the Interuniversity Attraction Poles Programme initiated by the Belgian Science Policy Office (IAP P7/08 CHARM). AKS acknowledges the support of DST-RFBR (INT/RFBR/P-117) and Indo-Austrian (INT/AUA/BMWFP-18/2013) project funds during the present research.
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This manuscript was prepared with the AAS L\LaTeX{} macros v5.2.
Fig. 1.— SDO/AIA 171 Å (top-left) and its difference image (top-right), which display the X6.9 flaring region, diffused plasma curtain formed by the unresolved thin loop threads, a narrow off-limb lane of the propagation of flare generated disturbances, and on-disk large-scale global disturbances, respectively by red, blue, green, yellow arrows. The bottom panel shows the STEREO-A EUVI 195 Å image showing the flaring region and western side core loops (indicated by black arrow) connecting two active regions. However, the less denser and more southwardly stretched diffused
Fig. 2.— SDO/AIA 171 Å difference image sequence showing the generation of the global coronal wave disturbances. The most of the disturbances propagate symmetrically in the southward direction.
Fig. 3.— Top three panels show the position of vertical slits over the plasma curtain, while bottom panels show their corresponding distance-time diagrams. From left-to-right, the slit positions are shifting away from flare energy release site.
Fig. 4.— The power spectral analyses of the transverse oscillations of deep layer of plasma curtain.
Fig. 5.— The power spectral analyses of the transverse oscillations of the surface of plasma curtain at middle (left) and on its southward direction (right).