Transverse oscillations in coronal loops observed with TRACE: I. An overview of events, movies, and a discussion of common properties and required conditions. ‡ §

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Abstract. We study transverse loop oscillations triggered by 17 flares and filament destabilizations; only 2 such cases have been reported in the literature until now. Oscillation periods are estimated to range over a factor of ~ 15, with most values between 2 and 7 min. The oscillations are excited by filament destabilizations or flares (in 6% of the 255 flares inspected, ranging from about C3 to X2). There is no clear dependence of oscillation amplitude on flare magnitude. Oscillations occur in loops that close within an active region, or in loops that connect an active region to a neighboring region or to a patch of strong flux in the quiet Sun. Some magnetic configurations are particularly prone to exhibit oscillations: two active regions showed two, and one region even three, distinct intervals with loop oscillations. The loop oscillations are not a resonance that builds up: oscillations in loops that are excited along their entire length are likely to be near the fundamental resonance mode because of that excitation profile, but asymmetrically excited oscillations clearly show propagating waves that are damped too quickly to build up a resonance, and some cases show multiple frequencies. We discuss evidence that all oscillating loops lie near magnetic separatrices that outline the large-scale topology of the field. All magnetic configurations are more complicated than a simple bipolar region, involving mixed-polarities in the interior or vicinity of the region; this may reflect that the exciting eruptions occur only in such environments, but this polarity mixing likely also introduces the large-scale separatrices that are involved. Often the oscillations occur in conjunction with gradual adjustments in loop positions in response to the triggering event. We discuss the observations in the context of two models: a) transverse waves in coronal loops that act as wave guides and b) strong sensitivity to changes in the field sources for field lines near separatrices. Properties that favor the model b are (1) the involvement of loops at or near separatrices that outline the large-scale topology of the field, (2) the combined occurrence of oscillations and loop translations, (3) the small period spread and similar decay time scale in a set of oscillating loops in one well-observed event, and (4) the existence of loops oscillating in antiphase with footpoints close together in two cases. All other properties are compatible with either model, except the fact that almost all of the oscillations start away from the triggering event, suggestive of an outward-pushing exciting wave more in line with model a. The spread in periods from event to event suggests that the oscillations may reflect the properties of some driver mechanism that is related to the flare or mass ejection.

‡ The associated movies on the CD-ROM can also be downloaded from http://vestige.lmsal.com/TRACE/POD/TRACEoscillations.html.

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1. Introduction

The phenomenon of transverse loop oscillations was discovered in a data set observed by the Transition Region And Coronal Explorer, *TRACE* (see the instrument description by Handy *et al.*, 1999), after two months of solar observing. This event was associated with an M4.6 flare on 14 July 1998 in NOAA Active Region 8270 (first described by Schrijver *et al.*, 1999, and later studied in detail by Aschwanden *et al.*, 1999). Since then, only one other event has been reported on (Schrijver and Brown, 2000), of which only the decay phase of the oscillation was observed on 4 July 1999.

The transverse loop oscillations discussed in the literature (interpreted as fast kink modes, see Roberts *et al.*, 1984, for an introductory discussion) present us with two significant problems. First, they decay very quickly on a time scale of the order of 15 minutes, at an oscillation period of about 5 minutes. Nakariakov *et al.* (1999) have argued that if this decay reflects coronal damping due to resonant absorption of global mode oscillations, then the characteristic Reynolds number is eight to nine orders of magnitude smaller than the classical value. Regardless of whether this is caused by a high viscosity or resistivity, such a low Reynolds number would require a significant shift in our views of coronal physics. De Pontieu *et al.* (2001), in contrast, argue that the decay is primarily due to leakage of the coronal wave into the chromosphere (see Hollweg, 1984, for an early description), which requires a better understanding of that coupling and of the role of the chromosphere as a boundary condition to coronal processes.

Second, the loop oscillations occur in only a small subset of the loops visible in the *TRACE* images, suggestive of a strong sensitivity to the details of the magnetic field configuration. This prompted Schrijver and Brown (2000) to study how coronal loops would respond to changes in the photospheric boundary conditions associated with a flare. They point out that field lines that pass near a magnetic null (and thus lie at or near a separatrix surface that delineates the boundaries of domains of magnetic connectivity) respond to a change in the location of the null point by a much amplified perturbation in their position. They envisioned a scenario in which a flare would rock the underlying photospheric flux concentrations, with associated changes in the positions of the set of null points. Only those field lines passing near null points associated with large-scale separatrices would then display oscillatory displacements of observable magnitude. In this model, the rapid decay of the oscillation is not a coronal phenomenon, but is instead a consequence of the decrease in the displacement of some of the flux concentrations in the photosphere.

Loop oscillations are also of interest as diagnostics for the strength of the coronal field. Nakariakov and Ofman (2001) discuss how the oscillation frequency might be used to infer field strengths in combination with the plasma density.

In view of these studies, our understanding of the solar corona, and of the responses of the coronal field to photospheric driving, can be significantly enhanced by studying loop oscillations. We have therefore subjected the *TRACE* data to extensive inspection, and have found 15 other time intervals in which oscillatory displacements of coronal loops are seen. In this paper, we discuss these events (in Section 3 and the Appendix) in order to find out under what circumstances loop oscillations occur; we identify a subset of particularly illustrative events in Section 3. We describe the events (shown on a set of movies on the CD-ROM), identify common properties (Sect. 4), and interpret the observations in view of proposed models (Sect. 5). The periods, amplitudes, and other quantitative details are discussed in a companion paper by Aschwanden, De Pontieu, Schrijver and Title (2002; paper II).

2. Instrument, observations, and data processing

TRACE (Handy *et al.*, 1999) is a normal-incidence telescope that images the solar atmosphere with a resolution of about 1.25 arcsec FWHM (Golub *et al.*, 1999), equivalent to 900 km. The telescope has a field of view of 1024×1024 pixels, each covering an 0.50 arcsec square. We use data from two EUV channels, centered at 171 Å (observing Fe IX and Fe X, peak sensitivity at 1 MK), and at 195 Å (Fe XII, 1.5 MK). The continuum contribution in these passbands can be ignored, except during strong flares. The 195 Å channel also contains an Fe XXIV line that is seen during substantial flares.

The list of loop oscillations in Table I was compiled based on two searches. First, we collected all cases identified in the routine daily inspection of *TRACE* data; we estimate that we have carefully inspected at least $\sim 25\%$ of the *TRACE* 171 Å data throughout the first three years of operations, while the *TRACE* team has viewed almost the entire data set. Second, we searched the compilation (by Kathy Reeves, Megan Gribbons, and Harry Warren) of 18 X-class flares, 141 M-class flares, and 96 C-class flares observed by *TRACE* prior to 15 June 2001, with at least 171 Å or 195 Å in the main observing cycle. One case is not listed in Tables I and II: (apparent) loop oscillations involving long loops arching over the X20 flare that occurred on 2 April 2001 around 22 UT. Unfortunately, the main flare event occurred at the edge of the field of view, making it hard to study loop connectivity. We note that

Table I. Observations of oscillations in coronal loops.[1]

Case	Date	Interval	$\langle \Delta t \rangle$	Time	AR	Trigger	Notes
1	14-Jul-98	12:45-13:44	75	12:57:38	8270	M4.6	a
(2)	30-Aug-98	18:00-18:12	36	18:04:44	8319	M1.3	b, c
3	23-Nov-98	06:10-07:29	33	<06:35:57	8384	X2.2	
4	4-Jul-99	08:00-09:00	43	<08:33:58	8611	C6.4	d
(5)	25-Oct-99	06:27-06:46	25	06:30:00	8739	M1.7	e
(6)	10-Feb-00	01:01-02:06	36	01:56:21	8858	C7.3	
7	23-Mar-00	11:30-12:00	15	11:35:43	8910	M2.0	
8	12-Apr-00	03:29-03:53	35	03:31:54	8948	M1.3	
(9)	25-Aug-00	14:22-16:17	69	14:46:28	9143	M1.4	b, f
10	21-Mar-01	00:31-03:37	71	<02:32:45	9373	M1.8	
11	22-Mar-01	03:48-05:41	54	05:13:23	9373	M1.0, fd?	b, g
(12)	12-Apr-01	10:16-10:34	30	10:16:23	9415	X2.0	
13	15-Apr-01	21:58-22:27	32	22:01:44	9415	fd, C5.1	h
14	15-Apr-01	22:46-23:14	70	<22:46:53	9415	fd	i
(15)	13-May-01	02:52-04:30	42	03:03:07	9455	M3.6	
(16)	15-May-01	01:43-03:32	53	02:57:41	9455	M1.0	
17	15-Jun-01	06:20-07:36	50	06:35:21	9502	C3.8	j

[1] Listed are: (1) identification (also movie) number, with the less clear cases between parentheses; (2) date; (3) time interval (UT) shown in movie; (4) average cadence $\langle \Delta t \rangle$ in the movie (seconds), excluding data gaps; (5) time (UT) of the first frame in which the oscillation is visible (<: data gap, or radiation-damaged frames, immediately prior to the loop oscillation); (6) NOAA active region number over which the oscillations occur; (7) triggering or associated event (fd: filament destabilization); (8) notes: (a) Both the 171 Å and 195 Å movies are shown; all other movies are in the 171 Å pass band, except for case 17. (b) All movies are at full resolution (0.5 arcsec pixels), except movies 2, 9 and 11, which are at half the resolution (CCD read out using 2x2 summing). (c) Trigger event occurs in AR 8307. (d) A data gap occurs around the time the oscillation was triggered; the start time of the flare is listed. (e) Trigger occurs in AR 8741. (f) Movie displayed with $\gamma = 0.5$. (g) Trigger is likely an M1.0 flare within the region, which may have been triggered by a distant filament destabilization. (h) Listed is the time interval for the shorter of two movies showing this event (compare case 14) (i) Listed is the time interval in which the 2nd oscillation is seen in this region (compare case 13). The entire movie covers the period from 13:04 UT to 23:50 UT. (j) Movie in the 195 Å pass band.

neither the daily inspection, nor the flare lists are exhaustive, so more cases of loops oscillations may yet be found in the data base.

For the present study, we have produced a set of movies (listed in Table II) in which the *TRACE* data were minimally processed: particle hits were removed using the standard median filter, the images were normalized to a standard exposure time, displayed with a γ factor of unity (except where otherwise noted), and shifted by an integral number of pixels to correct crudely for solar rotation. A clock was added to each frame. Some movies (as specified in the movie captions) were rotated over $\pm 90^\circ$.

The movies can be accessed via the associated hypertext file on the CD-ROM. The CD-ROM also contains sample magnetograms if available, links to a summary of all regions on the disk on the day of the event, and to the NOAA event listings. References to the relevant literature are provided via NASA's Astrophysics Data System.

3. Transverse loop oscillations

Cases 1, 3, 7, 10, and 13 provide a good sampling of the various types of oscillations and their excitations. This section describes these events, while the other cases are discussed in the Appendix.

3.1. Case 1: 14 July 1998

An M4.6 flare (with subsequent dimming of much of the corona surrounding the region that is suggestive of a coronal mass ejection, but this cannot be confirmed because of a lack of observations) triggers oscillations in multiple loops throughout the active-region corona. The flare occurs at the site of opposite-polarity intrusions near the center of the active-region complex.

At least three sets of loops exhibit clear, damped oscillations (discussed previously by Schrijver *et al.*, 1999, Aschwanden *et al.*, 1999, and Nakariakov *et al.*, 1999). Two of these sets (A and B in Fig. 1) are connected to narrow flare ribbons at the site of the leading spot (best seen in the movie frame at 01:07 UT), and one (labeled C) ends close to, perhaps at, a flare ribbon, while certainly connected to a fan of sunspot loops that changes dramatically in intensity during the flare. None of the oscillating loops end near a site where opposite polarities occur close together.

The two sets of loops arching over the flare site (B and C) exhibit oscillations that are close to fundamental standing waves. The third set (A), connecting to another, smaller active region in the south, is suggestive of two nearby loops moving essentially in antiphase following the initial perturbation. To the right (west) of this pair of loops (between the lines on either side of label D in Fig. 1), there are lower-amplitude oscillatory displacements.

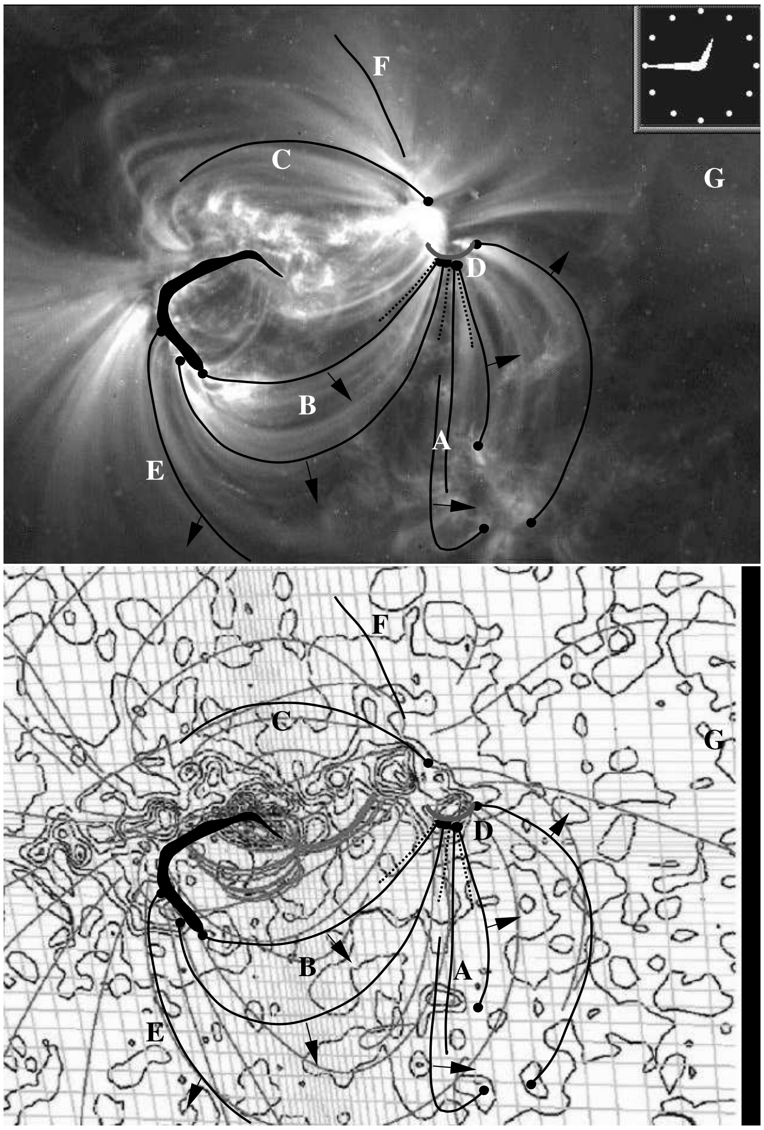

Figure 1. *Top:* First frame of the movie showing case 1, outlining oscillating loops observed on 14 July 1998, as discussed in Section 3.1. Solid lines outline coronal loops or boundaries of loop fans that exhibit oscillations (see text for details); dots at one or both ends indicate an estimated footpoint location. Dotted line segments separate sets of loops that connect to distinct patches of opposite polarity. A grey curve outlines a flare ribbon within the preceding sunspot. Arrows show the direction of the initial motion following the excitation where this can be determined unambiguously. A darkened area outlines the site of the initial phase of the impulsive event that likely triggered the oscillations. *Bottom:* A potential-field extrapolation (from Aulanier et al., 2000). The field lines are shown in grey. The dark contours outline the magnetic field (compare the color version on the CD-ROM). The lines and labels from the top panel are overlayed in black.

Table II. List of movies included on the CD-ROM.

- Movie 1a, b. a) 1998-Jul-14, 12:45-13:44 UT; M4.6 flare in AR 8270, 171 Å. b) Same event, seen in the 195 Å pass band.
- Movie 2. 1998-Aug-30, 18:00-18:12 UT; AR 8319, 171 Å; oscillations associated with small event in AR 8307; 2x2 summed pixels.
- Movie 3. 1998-Nov-23, 06:10-07:29 UT; X2.2 flare in AR 8384, 171 Å; images rotated over +90°.
- Movie 4. 1999-Jul-4, 08:00-09:00 UT; C6.4 in AR 8611, 171 Å.
- Movie 5. 1999-Oct-25, 06:27-06:46 UT; AR 8739, 171 Å. M1.7 in AR 8741 triggers oscillations in AR 8739.
- Movie 6. 2000-Feb-10, 01:01-02:06 UT; AR 8858, 171 Å; C7.3.
- Movie 7. 2000-Mar-23, 11:30-12:00 UT; M2.0 in AR 8910, 171 Å; images rotated over +90°.
- Movie 8. 2000-Apr-12, 03:29-03:53 UT; M1.3 in AR 8948; 171 Å.
- Movie 9. 2000-Aug-25, 14:22-16:17 UT; following an M1.4 flare at 14:21 UT in AR 9143, 171 Å; 2x2 binned pixels.
- Movie 10. 2001-Mar-21, 00:31-03:37 UT; M1.8 flare in AR 9373; 171 Å; images rotated over +90°.
- Movie 11. 2001-Mar-22, 03:48-05:41 UT; AR 9373, following nearby filament eruption and/or M1.0 flare; 171 Å.
- Movie 12. 2001-Apr-12, 10:16-10:34 UT; during an X2.0 flare in AR 9415; 171 Å.
- Movie 13 2001-Apr-15, 21:58-22:27 UT; AR 9415; following a filament destabilization; C5.1 flare starting at 21:59 UT in the northern part of AR 9415; 171 Å; images rotated over +90°.
- Movie 14. 2001-Apr-15, 13:04 UT - 23:50 UT; destabilization/eruption of a small filament, in the southern part of AR 9415; 171 Å; images rotated over +90°.
- Movie 15. 2001-May-13, 02:52-04:30 UT; M3.6 in AR 9455; 171 Å; images rotated over +90°.
- Movie 16. 2001-May-15, 01:43-03:32 UT; M1.0 flare in AR 9455; 171 Å.
- Movie 17. 2001-Jun-15, 06:20-07:36 UT; C3.8 flare in AR 9502; 195 Å.

Close inspection of this event suggests that transient transverse displacements, often in addition to significant positional shifts in loops, are more widespread than the earlier studies suggested. Notice, for example, that the loop fan in the southeast (near E in Fig. 1) exhibits oscillatory displacements as it fades from the *TRACE* 171 Å passband. Also, the faint structure visible in the northwest (near G) appears to exhibit some oscillatory behavior as it fades. And finally, we point out a structure (near F) where the loop fan sways back and forth perhaps three times in about 30 minutes as cool material slides down the field.

The oscillating loops in the southern half of the field lie at or near separatrix surfaces, based on the observations (1) that adjacent loops follow strongly divergent paths to connect to different magnetic concentrations, and (2) that they all end near a (relatively weak) flare ribbon associated with the preceding sunspot. To clarify this, we plot dashed curves in Fig. 1 between the sets of loops that connect to different patches of opposite polarity, as shown by the systems labeled A, B, and D. Note, moreover, that the field lines in fan D appear to extend along a ridge of mossy emission. We also show the position of the flare ribbon (best seen around 01:07 UT) as a thick gray curve in Fig. 1.

Aulanier *et al.* (2000) compare the coronal loop configuration to a potential field extrapolation (shown in Fig. 1). They conclude that the large-scale field in this region is not far from potential. The extrapolation supports our conclusions that the oscillating loops lie near separatrices, although the connectivity to the photospheric concentrations differs in detail. For example, the cool loop fan towards the west from D in Fig. 1 appears to lie over the southward fan that is contained between the two black curves on either side of D. In the first 15 min. of the movie, these two sets of loops slide over each other, or the loop connectivity changes, but - as in the simulated potential field - there are two sets of loops here separated by a separatrix.

Another example is loop E: the *TRACE* field of view does not extend far enough southward to see where that loop terminates, but the potential field extrapolation extends further south, and suggests that its path is very different from the oscillating loops near B. Although loop E fades rapidly after the flare, it is seen to sway towards the east. Both these observations suggest a separatrix or perhaps even separator somewhere between the eastern lower segments of loops E and B.

3.2. Case 3: 23 November 1998

Oscillatory motions are seen in a bundle of loops (between the solid curves in Fig. 2) apparently connected to the site of an X2.2 flare (label B), that is likely associated with a mass ejection. A rapid shift in the mean position of the loops exceeds the amplitude of the oscillatory motions, that are visible for about 2 periods before the data gap.

The loop oscillations in adjacent loops are somewhat out of phase. Moreover, even though phase differences along a given loop cannot be accurately determined, the oscillations do not resemble a standing (resonating) wave pattern.

Almost an hour after the initial event, the loops (in particular the loop tops) continue to oscillate (see the movie segment past 07:17 UT) with a period that we estimate to be close to nine minutes, but now

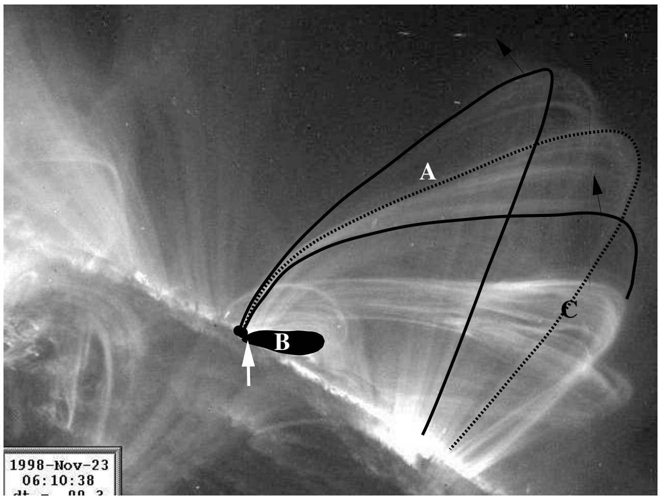

Figure 2. First frame of the movie showing case 3, outlining oscillating loops seen on 23 November 1998, as discussed in Section 3.2. The white arrow identifies the leftmost edge of the flare loop (as located by using the diffraction pattern seen at 06:43 UT).

at a low amplitude. Owing to a data gap from 6:48 UT until 7:17 UT, it is not known whether a secondary event triggered these oscillations. Whereas the NOAA event listings do show a B.9A event in AR 8384 at 7:12 UT, we point out that the initial amplitude of the oscillation was so large, that there would still be an observable oscillation left after an hour for a damping time scale of order 10^3 s (cf. paper II).

The magnetic configuration below the oscillations is of course unknown, but an earlier magnetogram (see CD-ROM material) suggests that there may be some large-scale mixed polarity near the preceding spot and within the polarity inversion zone. Nevertheless, we surmise that the oscillating loops are close to a separatrix, because (1) the paths of the field lines that appear to start from close to the flare site (the white arrow in Fig. 2) connect to separated flux concentrations (compare the solid and dashed lines in Fig. 2), and also because (2) the initial flare site and one side of the post-flare arcade appear to end at the footpoints of these high oscillating loops.

3.3. Case 7: 23 march 2000

A compact flare occurs near a set of cooling loops (connected to the flare ribbons) that display oscillations even as plasma cools into coronal rain. Adjacent loops are somewhat out of phase.

Note that the loops lie very near to a cusp in the magnetic field, which shows up very well in the movie after about 11:50 UT (the dotted

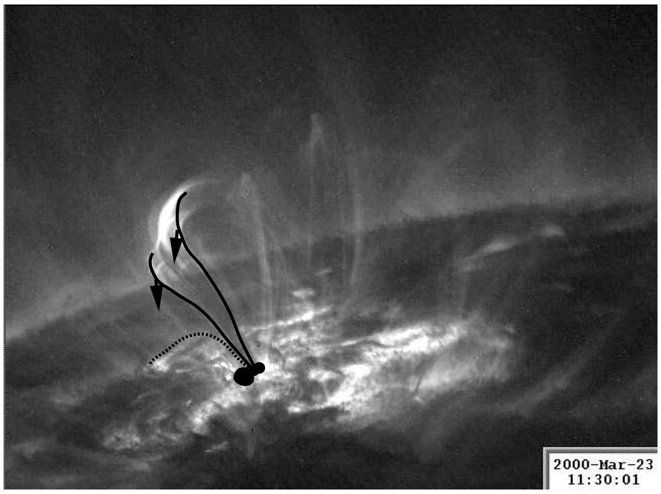

Figure 3. First frame of the movie showing case 7, outlining oscillating loops observed on 23 March 2000, as discussed in Section 3.3.

line in Fig. 3 outlines the first loop that shows up below the cusp). The loop ensemble shifts toward the cusp, as might be expected of loops at or very near a magnetic separatrix surface.

The first displacement of the oscillatory motions is downward. As the flare site is essentially underneath the loop segments that exhibit the oscillations most clearly, it is not clearly in the direction of the eruption site.

3.4. Case 10: 21 March 2001

The loop oscillations in this case are associated with a nearby filament destabilization. The M1.8 flare, starting at 02:28 UT and peaking (in X-rays) around 02:37 UT, was associated with a spray of cool material (likely the result of the eruption of a small filament): material is thrown up to a height of approximately 50,000 km, but much of it is subsequently seen to slide back down.

The oscillating loops exhibit significant phase differences between adjacent loops, but it is unclear whether there are phase differences along any given loop. The bases of the oscillating loops are difficult to identify, but likely lie on the extension of the ridge from which the filament erupts. Note that the leftmost of the oscillating loops identified in Fig. 4 clearly ends next to the site of the eruption; the other loops may end further away on the ridge, or may end near that same site, thus forming part of a curved surface.

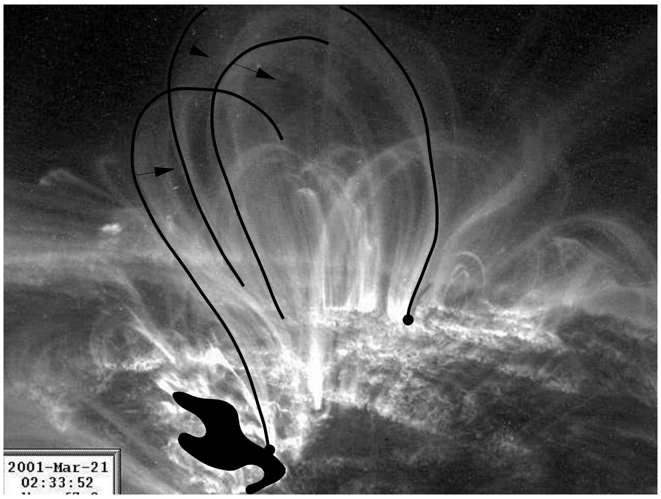

Figure 4. Frame of the movie showing case 10, outlining oscillating loops observed on 21 March 2001, as discussed in Section 3.4.

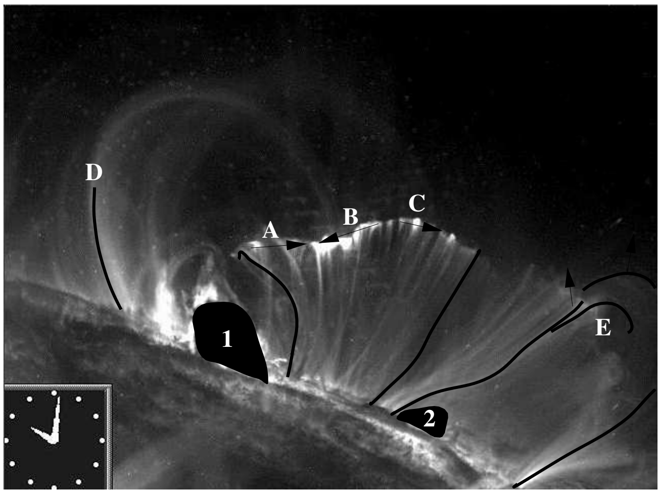

Figure 5. Frame of the movie showing case 13, outlining oscillating loops observed on 15 April 2001, as discussed in Sections 3.5 and in Appendix N.

3.5. Case 13: 15 April 2001

Oscillations are seen in a post-flare arcade associated with a series of events that followed an X14.4 flare that started at 13:19 UT. The post-flare arcade shows up in the *TRACE* 171 Å pass band somewhere between 14:18 and 14:40 UT, perhaps associated with a subsequent event at 14:38 UT (see NOAA event listings). At the time of the oscillations, the arcade is still increasing in height (suggestive of continuing reconnection and cooling), although much more slowly than in the initial phases when the loop-top heights rapidly increased with time. The oscillations in this very long-lived arcade were triggered by the destabilization of a nearby, relatively small filament (label 1 in Fig. 5).

The initial direction of the oscillation near A (Fig. 5) is away from the eruption (at label 1). Further along the arcade (near C), the initial motion is away from that event also, but in between (near B), the initial displacement - admittedly difficult to determine - is likely towards the filament eruption.

The amplitude of the oscillations decreases quickly, both in time (on a time scale of some 15 minutes) and in distance (being visible over less than 100,000 km). The loop top motions show a harmonica-like motion (with a period of approximately 4 minutes, apparently superimposed on a longer period, see paper II), suggestive of a nearly standing wave with decreasing amplitude in space and time, despite the differences in brightness, and therefore density and Alfvén speed. Note the high-frequency, low-amplitude ripples superimposed on the larger oscillation, introducing motions both along and perpendicular to the loop-top ridge. It remains to be studied whether any given loop shows phase differences between high and low segments.

Notice that in the long movie, there are a few loops to the left and above the X14.4 flare that can be seen to oscillate in the background between approximately 13:55 and 14:15 UT (loop segment D in Fig. 5).

4. Discussion

We identify 17 events associated with one or more loop oscillations. Of these, 10 of are well-shown by the *TRACE* image sequences, and moreover occur entirely within the field of view. The oscillation periods range from approximately 2 min. to 10 min., and one rather poor case has a period close to 35 min. (see paper II for precise measurements).

Conditions under which loop oscillate

The number of clearly oscillating loops associated with an event is always rather small, with nearby other loops often not responding, or with only particular domains responding to the oscillations. In all cases, the magnetograms show a magnetic environment that is more complicated than a simple bipolar configuration, showing either multiple polarities within the environment, or an irregular polarity-inversion zone. Whether this is a prerequisite for loop oscillations remains unclear; it may simply be required for significant and rapid reconnections to occur that can provide a sufficiently strong field perturbation to trigger the oscillations.

In almost all cases we find evidence that the oscillating loops lie at or near large-scale separatrices or near sites involved in reconnection, either because adjacent loops connect to different magnetic concentrations, or because the oscillating loops end near flare ribbons.

Excitation of the oscillation

The excitation of the oscillation can be in response to an event that can be at a loop base (as in case 7) or at some distant site (e.g., case 1). In case 11, we are left wondering whether it was triggered by the distant filament eruption or by an M1.0 flare internal to the region, which itself may have been triggered by that distant event. Some exciting events occur in nearby but not directly connected loops (as in case 14), others in magnetically connected loops (as in case 1). Some eruptions involve opening/closing configurations (as suggested in case 17), but in others no clear signs of a mass ejection are seen. Some magnetic environments are particularly sensitive to loop oscillations: three regions show two or three such events (cases 10 and 11 in AR 9373; cases 12, 13 and 14 in AR 9415; and cases 15 and 16 in AR 9455).

Key to the excitation of loop oscillations is a rapid adjustment or perturbation of the magnetic field: loop oscillations have never been observed under quiescent conditions.

The relative frequency with which a flare triggers an observable loop oscillation is $5.9 \pm 1.5\%$. This is likely a lower limit, because often the exposure times of *TRACE* are lowered automatically as the flare brightens, so that the fainter loops often disappear into the detector noise. There is a marginally significant trend of a larger likelihood for loop oscillations resulting from larger flares: $4 \pm 2\%$ of C-class flares are associated with loop oscillations, compared to $6 \pm 2\%$ of M-class flares, and $11 \pm 8\%$ of X-class flares ($16 \pm 9\%$ if the X20 flare on 2 April 2001 is included that was mentioned in Section 2 but not included in our study). The dependence of oscillation amplitude on the magnitude of the flare is not obvious from the movies (cf. paper II).

Longer-term behavior of oscillating loops

Often we see a substantial shift in the mean position of the loops in addition to the loop oscillations; such shifts are much more common than the oscillations (see, e.g., Schrijver *et al.*, 1999, and Priest and Schrijver, 1999, for examples). In most cases, the oscillating loops are likely involved in, or very close to, a reconnecting loop system, as they are either anchored very near to flare ribbons, or are part of post-flare arcades; others lie near bifurcation points where nearby field lines connect to different, well-separated sources.

Evolution of the amplitude

Visual inspection of the movies suggests that the initial excursion is always the largest (see paper II for detailed measurements). In all cases but one for which the direction of the initial displacement could be unambiguously identified, that motion was away from the site of the flare or filament destabilization that triggered the oscillation. This is suggestive of an excitation front moving away from the site of the eruption. In 6 cases (4, 7, 8, 10, 11, and 17), however, there is no evidence that such a front exists: it appears that only the oscillating loops are affected by the eruption. In other cases, there is evidence for such a front (sometimes a filament eruption) that affects only loops in a particular domain of the active region corona. Case 1 is the clearest case of an excitation that occurs throughout the active-region corona (see Aschwanden et al., 1999, for a detailed discussion).

All loop oscillations decay rapidly. Those with periods in the domain of approximately 3 to 10 min. are visible for only about 2 to 3 full oscillations. All loop oscillations occur in relatively high loops, with loop top heights exceeding approximately 60,000 km - case 13 - up to about 150,000 km - case 3. We point out that this may be a selection bias: only such high loops show up as quasi-persistent features in *TRACE* images taken in the passbands that are most sensitive to emission from plasma at about 1-1.5 MK.

Phase differences

The phase differences along oscillating loops are generally small, but are noticeable in a number of cases, and particularly strong in case 15. Even though the triggers often excite preferentially the fundamental mode, higher-frequency perturbations are not infrequently superimposed on the fundamental mode (particularly clearly in case 14).

Not all oscillating loops are in phase during any given event, even when they appear to end at nearby locations in the photosphere (see cases 10 and 15 for clear examples). In two cases (numbers 1 and 4), nearby loops are observed to be very nearly in antiphase.

Brightness changes

Oscillating loops are often seen to change in intensity during the oscillation. In case 7 the loop plasma is seen to cool rapidly, forming dark coronal rain. In case 1 some of the loops (near B in Fig. 1) drain as hot, bright material slides towards the photosphere.

5. Conclusions

What kind of phenomenon is the oscillating loop? Loop oscillations are triggered only by flares and filament eruptions, i.e. by phenomena in which there are likely to be significant Lorentz forces acting within the corona, in association with rapid field adjustments. Loop oscillations often occur at considerable distances from flare or eruption sites, so that the Lorentz forces acting directly on fields connected to these processes cannot always drive the oscillations. Instead, they drive field perturbations that propagate through the surrounding coronal field, although far from isotropically: in many cases only a particular domain of the field is affected, while in six cases (see Section 4) only the oscillating loops display motions.

We argue in the preceding sections that all loops that are seen to oscillate have at least one footpoint in the immediate vicinity of a separatrix surface or of a flare ribbon (likely the footprint of a volume of reconnecting field lines); of all such loops, a relatively small subset is seen to oscillate. Note that the separatrices involved delineate the large-scale structure of the field; most of the separatrices and associated (near) null points between, for example, the flux concentrations within a single polarity are not involved in this process.

Schrijver and Brown (2000) argue that field lines in the proximity of separatrices are much more sensitive to changes in field sources than are field lines that lie well within domains of connectivity. They used potential-field extrapolations to demonstrate that field lines close to or on a separatrix surface (or, equivalently, field lines passing close to a magnetic null point) exhibit strongly amplified displacements in response to small displacements in the photospheric charges; in this interpretation, all field lines in an active-region corona would be excited by the explosive event, with field lines adjacent to the oscillating loops oscillating at comparable amplitudes, but not observable because of a contrast in temperature, density, or both. We expect that the same is true in a non-potential environment, where field lines adjust in response to changes in the photospheric boundary conditions as well as to changes in coronal current systems.

If, on the other hand, the loop oscillations are free, fast kink modes (as suggested by Nakariakov *et al.*, 1999; see also Roberts *et al.*, 1984), then the oscillating loops should be surrounded by a low-density volume, in order for the waves to be able to propagate primarily along the loops without immediately radiating their energy into the surrounding coronal field. The fact that the oscillating loops stand out in the images is consistent with such a density contrast, although temperature contrasts may explain part of this contrast.

This brings us to the question what causes the oscillation and its decay. Nakariakov *et al.* (1999) assume that we are seeing a resonant mode that is rapidly damped by strong dissipation in the corona. Schrijver and Brown (2000), on the other hand, suggest that the oscillation and its rapid decay could reflect photospheric properties: a rapid reconnection of atmospheric field near the solar surface could briefly impart momentum on one or more photospheric flux concentrations, which would then rock a few times in the photospheric plasma before the associated wave motion propagates away, weakening in amplitude as it spreads from the flare site; the associated coronal-field perturbations, most prominent on field lines passing near null points, would decay with the fading of that motion. Interestingly, their model predicts that nearby loops that lie on either side of a separatrix would move in opposite directions; this would be consistent with the oscillations of nearby loops in antiphase that are seen in two cases (1 and 4).

It is interesting to note that in order for the latter mechanism to give the common (but not general) impression of a nearly standing wave, the expected Alfvén crossing time should be short relative to, or at most comparable to, the oscillation period in order to make the entire loop behave essentially in phase with the changes in some localized driver. The time it takes Alfvén waves to travel from one end of a coronal loop to the other is a function of the Alfvén velocity (km/s)

$$v_{\rm A} \approx 10^4 B_{100}/\sqrt{n_9}, \tag{1}$$

where B_{100} is the field strength in units of 100 gauss, and n_9 the electron density in units of $10^9\,{\rm cm}^{-3}$. The Alfvén crossing time $t_{\rm A}$ (s) of a loop of length ℓ_{10} (in units of 10^{10} cm, or 10^5 km) is then

$$t_{\rm A} \approx 10\,\ell_{10}\sqrt{n_9}/B_{100}. \tag{2}$$

If we combine this with the RTV scaling law for quasi-static loops ($T_{\rm a,6} = 2.8(n_{\rm a,9}\,\ell_{10})^{1/2}$, for apex temperature $T_{\rm a,6}$ in units of 10^6 K; Rosner *et al.*, 1978) in order to introduce an approximate relationship between plasma density and loop length, we find that

$$t_{\rm A} \approx 3.5\sqrt{\ell_{10}}\,T_{\rm a,6}/B_{100}. \tag{3}$$

Well above an active region, the magnetic field is likely to be of order 10-30 gauss. For a loop apex height of $\sim 50,000 - 150,000$ km, and an apex temperature of the order of 1 MK (for which the loop is observable with the *TRACE* 171 Å and 195 Å channels), the time it would take an Alfvén wave to travel back and forth along the loop is approximately $2t_{\rm A} = 80 - 300$ s. This time scale overlaps with the low end of the range of periods of the oscillating loops (see paper II for details), and is thus

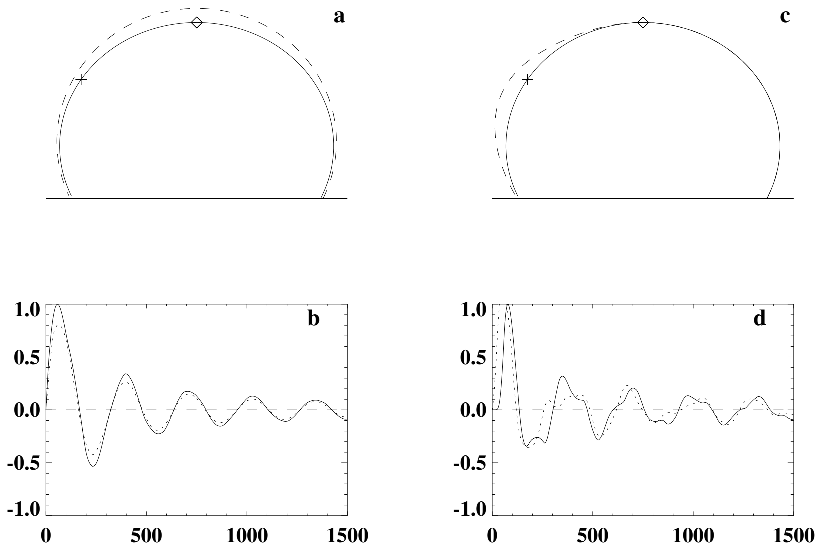

Figure 6. Illustration of oscillations in coronal loops. Panel *a* shows the equilibrium configuration of a coronal loop (solid curve) that is initially perturbed in a way that is not too different from an oscillation in the fundamental resonance (dashed line). The position history of the loop top (diamond in panel *a*), is shown by the solid line in panel *b*, and for a point lower in the loop (+) by the dotted line. Panels *c* and *d* are for an asymmetric excitation

consistent to first order with the model. If the field is rocked by an eruption that is rather close to one side of the loop, propagation effects are likely to be more pronounced than when a distant driver rocks the field.

Let us now consider the case of impulsively-excited kink waves in the coronal field. In the context of this model, how could it be that so many of the observed loop deformations resemble fundamental standing waves, whereas the damping time scale is only a few times the oscillation period. We suggest that this is because the initial perturbation affects much of the loop, while the loop base remains anchored in the photosphere at essentially the same position. In such a case, the initial loop distortion resembles the profile of a fundamental standing wave. If, in contrast, the excitation were to occur at some preferential location, say near one of the footpoints, then multiple frequencies would be present throughout the observable part of the decaying oscillation, because the higher frequencies would not decay fast enough compared to the fundamental mode for the compound motion to closely approximate a simple fundamental mode. This difference is illustrated in Fig. 6, for a model of a string of coupled oscillators, for which the restoring force is proportional to the local curvature, while damping in this model occurs everywhere along the string, and the endpoints are fixed (note that leakage of the signal through the endpoints would yield a similar result). There is no dispersion in this model, as for a simple Alfvén wave, whereas an MHD kink mode propagating along a tube has a wavelength-dependent phase speed that can range over at most $\sim 40\%$ of the Alfvén speed in cases with a large density contrast between interior and exterior of the oscillating tube (Roberts et al., 1984).

Fig. 6*a* shows a case for which the equilibrium configuration of a coronal loop (solid curve) that is initially perturbed in a way that is not too different from an oscillation in the fundamental resonance (dashed line). The position history of the loop top, shown by the solid line in panel *b*, resembles an exponentially damped, nearly sinusoidal oscillation; the phase differences along the loop are small, as can be seen from the oscillation history lower down in the loop (+ in panel *a*), shown by the dotted curve. In case the excitation deviates strongly from the fundamental mode, as for the asymmetric excitation shown in panel *c*, multiple spectral components will show up, and the oscillation may look like the curves shown in panel *d*. Note that there are now significant phase differences between different positions along the loop.

We can thus argue in both scenarios that distant events are more likely to produce loop oscillations like the standing fundamental model, whereas nearby ones are more likely to yield phase differences along the loops. We actually observe this difference: when oscillations are excited from well away from the footpoints, the loops appear to be in a fundamental standing mode (best seen in case 1), while if they are excited from near to one of the footpoints, multiple frequencies and phase differences are seen (good examples are cases 7 and 10).

One key distinction between the mechanisms for the coronal oscillations described above is that in the case of a kink mode, there should be a well-defined dispersion relationship between wavelength, period, and propagation velocity (probably involving plasma parameters both inside and outside the loops). The quantitative study of loop oscillations required to establish such a relationship is started in paper II. Unfortunately, the lack of field-strength diagnostics and uncertainties in local plasma-density measurements severely complicate the quantitative conclusions.

Alternatively, in the case of a sensitive dependence of some loops to a damped oscillation in one or more field sources, as proposed by Schrijver and Brown (2000), the periods and damping time scales of oscillating loops in a given event should all be the same. There is only one case (no. 1) in which multiple loops clearly oscillate. In that case, the periods in 5 oscillating loops analyzed by Aschwanden *et al.* (1999) have a standard deviation of only 9%. The three loops (at A, below B, and at C in Fig. 1) that remain visible longest, have oscillations that persist until about $35 - 40\,$min. after the flare. The differences from loop to loop are small, yet the oscillations occur in different magnetic environments, in loops with estimated lengths that covered a range of a factor of 1.8.

The fact that we now have oscillation periods spanning a factor of about 3 (or 15 if we include one poorly defined case), suggests to us that the oscillatory behavior is controlled by something related to the flare or eruption, rather than that field rocks with the photospheric cutoff period as Schrijver and Brown (2000) proposed as the cause for the null-point displacements.

The idea proposed by Schrijver and Brown (2000) is consistent with the fact that the mean position of the loops is often seen to change. This translation often exceeds the oscillation amplitude. In the commonly held view, flares and filament eruptions dissipate or redirect coronal currents (themselves sources of coronal field). If these changes are fast, then damped oscillatory changes are likely induced in analogy to (coupled) LCR circuits. If, on the other hand, the evolution of the current systems is relatively slow, as in the case of convection-driven translations of the photospheric sources, only loop translations would be observed (which are very common in *TRACE* data sets).

In summary, we conclude that the observed loop oscillations are not resonances that build up after an initial excitation. We find support for the concept that the oscillations reflect that certain field lines are particularly sensitive to changes in the field sources in the involvement of loops at or near large-scale separatrices, the combined occurrence of oscillations and loop translation, the small period spread in one well-observed case, and the existence of loops oscillating in antiphase with footpoints close together. The spread in periods from case to case suggests that the oscillations are perhaps somehow driven rather than free oscillations. The fact that almost all of the oscillations start away from the triggering event, on the other hand, suggest that some outward-pushing wave excites them. All other properties are consistent with either of the two models discussed.

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Appendix

This appendix contains the descriptions of the cases not given in the body of the paper. The clearest cases of loop oscillations (see Table I) are identified by underlined dates in the subsection titles.

A. Case 1: 14 July 1998

. See Sect. 3.1.

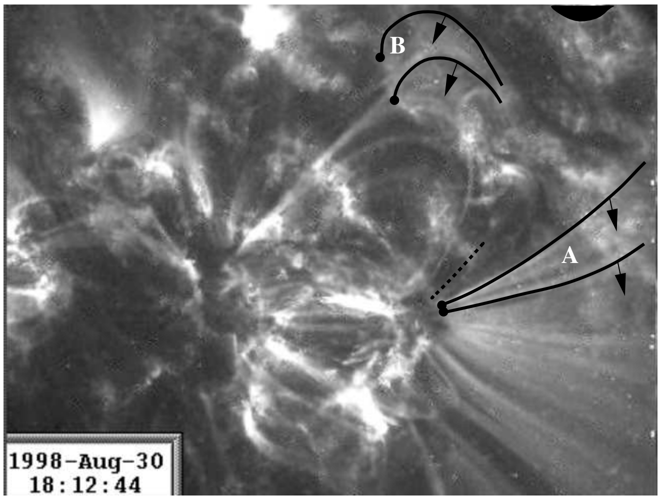

Figure 7. First frame of the movie showing case 2, outlining oscillating loops seen on 30 August 1998, as discussed in Section B. The loops on either side of the short, dashed line segment connect to different patches of opposite-polarity flux, and must therefore be close to a separator. See the caption to Fig. 1 for further details.

B. Case 2: 30 August 1998

A compact flare, which occurs in the northwest corner of the *TRACE* field of view in NOAA AR 8307 (observed at lower resolution using 2x2 summing while reading out the *TRACE* CCD), appears to excite oscillations in a sunspot fan in a region further to the south (bounded by the lines on either side of label A in Fig. 7); less clear are some deformations in an arcade of loops that arch from Active Region 8319 in the center of the image to AR 8307 in the northwest (B in Fig. 7). Note that NOAA lists an M1.3 to occur in AR 8319 at 18:00 UT, whereas *TRACE* data suggest the flare occurred in AR 8307.

The more clearly oscillating sunspot loops (at label A) are only partially contained in the field of view so that their conjugate footpoints cannot be identified unambiguously; possibly, they connect to the flare site in AR 8307.

The oscillating loops are likely adjacent to a separator (somewhere near the dotted line in Fig. 7): loops northward of the oscillating loops most likely connect to the following polarity within AR 8319, while fan A likely connects to AR 8307. Between 18:06 UT and 18:08 UT there is a small brightening that occurs at what may be the base of that separatrix.

C. Case 3: 23 November 1998

See Sect. 3.2.

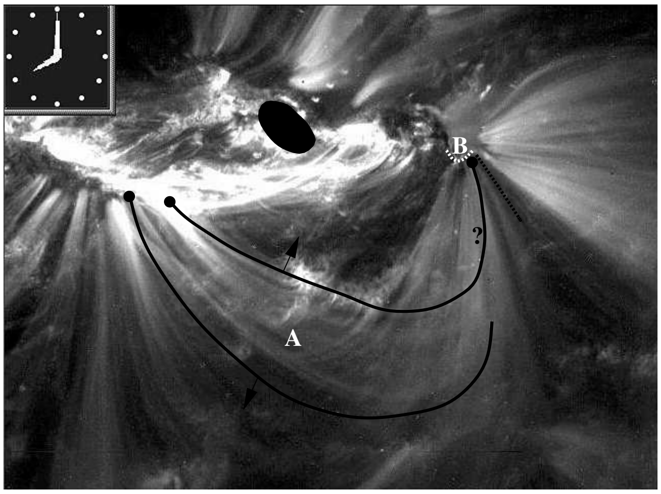

Figure 8. First frame of the movie showing case 4, outlining oscillating loops observed on 4 July 1999, as discussed in Section D. The two solid, black curves identify the outer edges of a loop system that exhibits oscillations, with these boundaries essentially in antiphase. The dashed, white curve near B shows the location of a flare ribbon. The loops on either side of the dashed line segment look like they connect to different regions, suggesting of a nearby separator.

D. Case 4: 4 July 1999

The observations of this event (first discussed by Schrijver and Brown, 2000) cover only the damping part of the loop oscillations. Some loops oscillate in the fundamental standing mode, but with nearby loops in antiphase (compare the loops near the boundaries of the oscillating system outlined by the lines in Fig. 8). Other loops merely move monotonically, or remain stationary throughout the movie.

The oscillating loops appear to be connected to the field involved in the flare: on the left (east) the loops end on or very near a bright ridge that is likely the basis of a sheared flare-related arcade (directly connected to the flare site over the mixed-polarity area in the center of the region), while on the right (west) the loops end in a faint ribbon that develops within a sunspot (note that this ribbon remains visible throughout the hour-long interval spanned by the movie).

The preceding (western) side of the oscillating loops end near a ribbon that is close to a field bifurcation: some loops that probably lie below the oscillating ones, leave the field of view shown in the movie, but appear to connect to different flux concentrations than the oscillating loops (although possibly to the same cluster of following polarity). On the following side, the oscillating loops end close to a negative (black) polarity intrusion at the southern edge of the bulk of the flux, also indicative of the presence of nearby separatrix surfaces near the footpoints of the oscillating loops between the footpoints of the compact loops that likely close on this opposite-polarity intrusion and those connecting to the more distant preceding polarity.

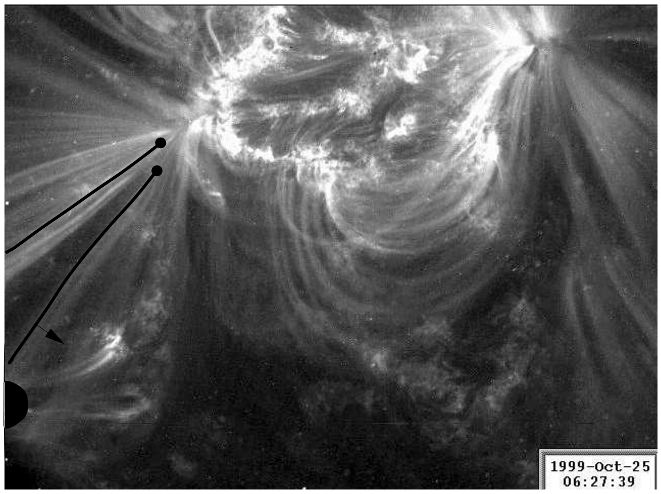

Figure 9. First frame of the movie showing case 5, outlining oscillating loops observed on 25 October 1999, as discussed in Section E.

E. Case 5: 25 October 1999

An M1.7 flare and associated activity at the south-eastern edge of the field of view, excites low-amplitude, but apparently high-frequency oscillations in two loops in a fan pointed towards the southeast, possibly connecting to the flare site. The oscillations are visible only in those parts of the field line fan that end at two segments of the flare's ribbon complex (see the images around 06:32 UT).

F. Case 6: 10 February 2000

Loops are observed to move rapidly in response to a filament destabilization within the active region (with material swirling down into a

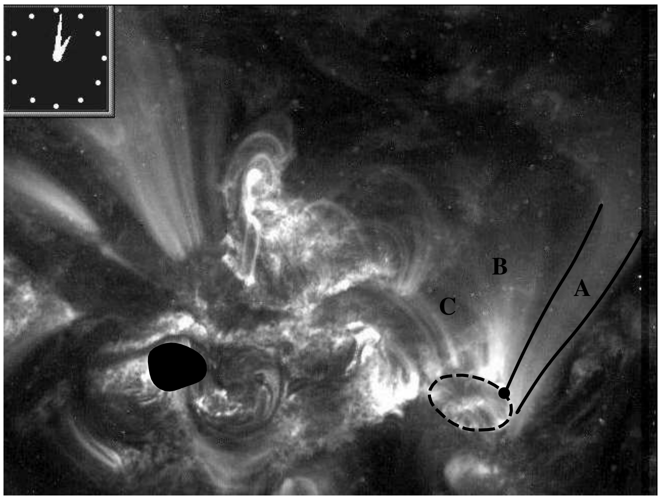

Figure 10. First frame of the movie showing case 6, outlining oscillating loops observed on 10 February 2000, as discussed in Section F. The dashed curve shows the contour of an anemone configuration, from the edge of which the oscillating loops emanate.

spot), but it is not clear whether there is a true oscillation superimposed on the motion.

The event involves only loops of which we see the lower segments starting on the righthand (western) edge of the field of view. The loops involved arer anchored near the edge of an anemone configuration in which the sunspot is entirely surrounded by opposite-polarity field (the outer perimeter of this, the intersection of the separatrix and the photosphere, is shown by a dashed curve in Fig. 10). The edge of this anemone configuration shows a minor brightening on the upper right (where the loops connect to the photosphere), likely associated with the much clearer flare ribbon on the lower left of the anemone structure.

Whereas the magnetic connectivity is unclear, notice how the loops near C in Fig. 10 close fairly low over a polarity-inversion zone to flux in the preceding side of the following polarity, while loops near B and C arch much higher to an unidentified patch of flux. Notice also that around 01:55 UT a loop segment appears just below label C that also shows oscillatory motions superimposed on its translation.

G. Case 7: 23 march 2000

See Sect. 3.3.

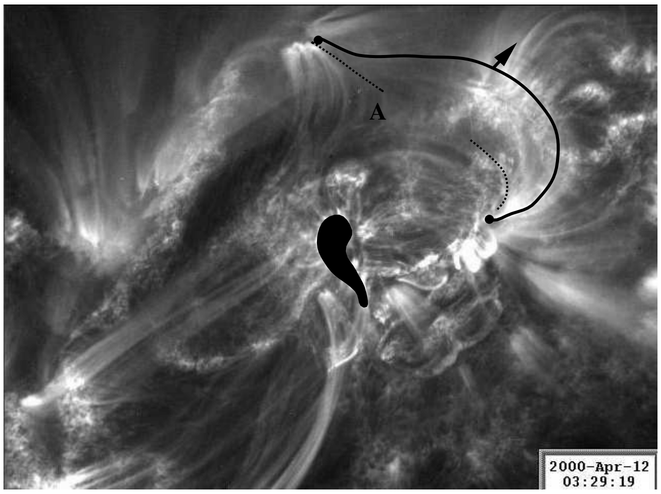

Figure 11. First frame of the movie showing case 8, outlining oscillating loops observed on 12 April 2000, as discussed in Section H.

H. Case 8: 12 April 2000

A constrained eruption in the core of the active region causes significant distortion in the loops connected to the multiple ribbon sites. To the south, a high, long loop system distorts, but does not show an obvious oscillation. To the NE, however, a fan of fairly faint loops (connected to or ending very near ribbons on both ends) shows a moderate-frequency oscillation while the loop system expands (Fig. 11 outlines the clearest of these loops).

The northern end of the loops lies close to loops that connect to a much nearer collection of opposite-polarity flux, suggesting that the oscillating loops lie close to a magnetic separator (the upper dotted curve in Fig. 11); in fact, there is likely a second separator on the other side of these loops, because the loops on that side connect to a third set of photospheric concentrations. The movie suggests that there is a reconnection event near label A in Fig. 11, which involves what are likely separators as outlined by the two dotted curves in the figure.

I. Case 9: 25 August 2000

This is a case of oscillation in high-arching loops, with phase differences suggestive of a propagating wave. High over the active region, diagonally towards the upper-left corner from the flare site, there are some loop bundles that oscillate about two periods before the motions disappear again. The connectivity of the loops to the flare site is unclear

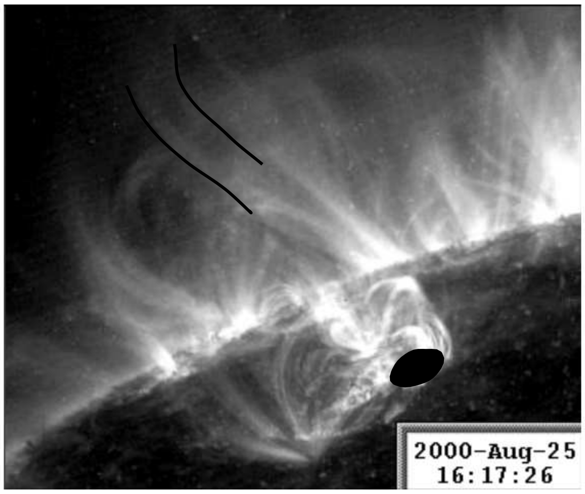

Figure 12. First frame of the movie showing case 9, outlining oscillating loops observed on 25 August 2000, as discussed in Section I.

because of line-of-sight confusion, but the lower visible segments of the oscillating ensemble points toward the limb-ward edge of the post-flare arcade. There are no signs of a filament ejection, although the high corona does show clear signs of reconfiguration. The high loops are so faint, that a normal intensity scale would not have shown them; the contrast in the images had to be reduced considerably (low γ value) to bring out these oscillating loops.

J. Case 10: 21 March 2001

. See Sect. 3.4.

K. Case 11: 22 March 2001

A distant erupting filament (labeled A in Fig. 13) "catapults" material and field towards AR 9373. It seems that as that signal reaches the field over AR 9373 it excites oscillations in various loops. Although it is suggestive that this is the cause of the subsequently observed loop oscillation over the limb, a flare is seen in the *TRACE* passband (initially by a diffraction pattern of the bright kernel) at the limb in AR 9373 (near E) starting around 5:18:37 UT. This is likely the EUV signature of the M1.0 flare listed by NOAA to have started at 05:05 UT. The first signs of field distortion are seen at 05:12 UT (in the loops just above label B), and the first displacement in the oscillating loops happens

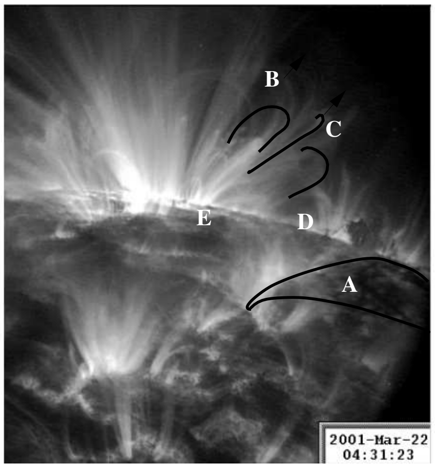

Figure 13. Frame of the movie showing case 11, outlining oscillating loops observed on 22 March 2001, as discussed in Section K.

between the exposures at 05:12:37 UT and 05:13:23 UT. Hence, it may be that the distant filament triggered the M1.0 flare, or maybe not, but the loop oscillations are likely the consequence of the flare in the core of the active region corona.

Some high loops (as near B) clearly distort, but it is not clear whether they really oscillate. Others (as the three loop segments outlined near C) clearly oscillate as they shift in position.

The oscillations primarily affect the high parts of the system, with clear phase differences between the excited loops. Note that two loops to the right and below the most obviously oscillating high loops (near D) also show brief signs of oscillatory disturbances; these loops appear to lie near a bifurcation point on either side of a connectivity change where loops close either back onto AR 9373 or onto a faint, unnumbered region to southwest (right) of it.

L. Case 12: 12 April 2001

This is a case of coronal field deformation with an oscillatory component, most clearly seen to in a west-north-westerly direction (near A in Fig. 14) prior to about 10:26 UT. Loop segment B also displays some oscillatory component; it is unclear whether B is the extension of A, or even where the footpoint of segment B really is.

Note that the coronal loops ending on the ridge to the northwest of the sigmoid flare kernel (fan C) all shift significantly in position, but without an oscillatory component.

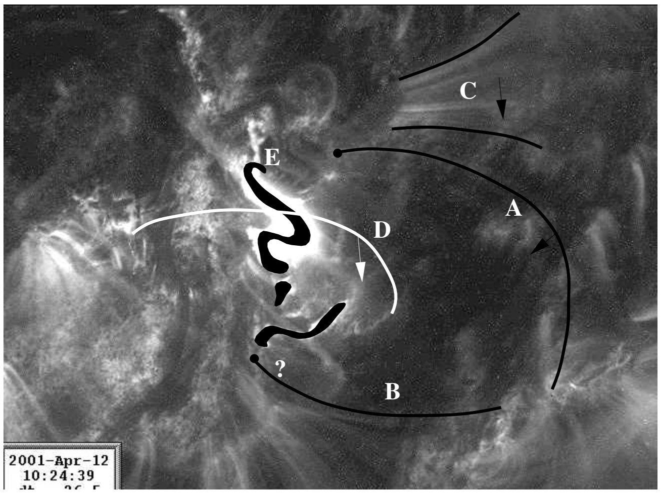

Figure 14. Frame of the movie showing case 12, outlining oscillating loops observed on 12 April 2001, as discussed in Section L.

Loops ending in the relatively weak ribbon due east of the flare site (roughly outlined by the white curve labeled D in Fig. 14) are seen to move rapidly, most clearly in a region immediately west of the flare kernel. Note also that the northern extremity of the sigmoid structure (E) reconnects between 10:20 UT and 10:22 UT when it is seen to flip over to another footpoint.

This is one of only two cases (with case 7) in which the initial motion is not clearly directed away from the site of the eruption or flare. The initial displacement in this case may well be associated with the deformation of the magnetic field around D (Fig. 14), however, rather than that it is the first part of the oscillatory motion.

M. Case 13: 15 April 2001

See Sect. 3.5.

N. Case 14: 15 April 2001

Just before 22:40 UT, a small filament eruption is seen near the right-hand (southern) end of the post-flare arcade that resulted from the X14.4 flare that started at 13:19 UT (label 2 in Fig. 5). The loops forming this part of the arcade appeared only shortly before the nearby filament eruption; it is unclear whether they are directly involved with the large flare that caused the arcade, but they clearly form an extension of it. The contained eruption around 22:40 UT excites small-amplitude oscillations that are most clearly visible at the loop tops near the righthand edge of the field of view. The image cadence is rather low to allow the oscillation period to be measured accurately (notice that the interval between successive image roughly doubles after 22:46 UT).

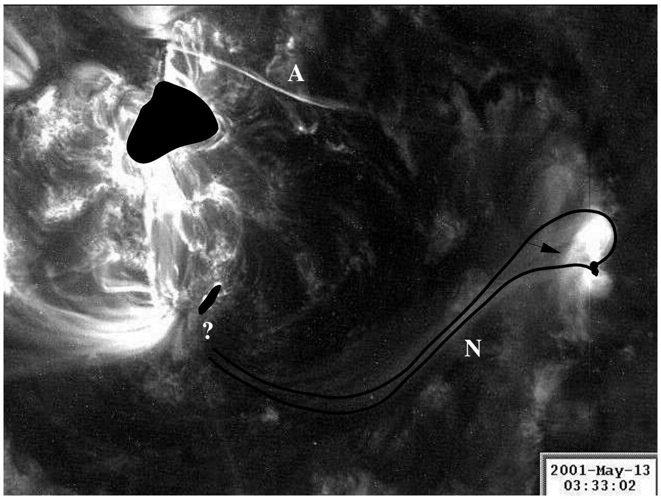

Figure 15. Frame of the movie showing case 15, outlining oscillating loops observed on 13 May 2001, as discussed in Section O.

O. Case 15: 13 May 2001

A flare and eruption occur in the western part of the region, while in the southern part (to the right in the movie) there are some long loops connecting to a distant compact magnetic region of apparently a single polarity. It is unclear where the footpoins are of these oscillating loops within the active region, but they may be at or near a compact ribbon site (near the question mark in Fig. 15). Shortly after the excitation, the loops settle into a mode with a node midway the loops (near N in Fig. 15).

Note that around 3:33 UT a connection lights up (label A in Fig. 15) between a magnetic concentration just westward of that single polarity, connected to flux on the preceding part of the flare ribbon (at the top of the movie frames).

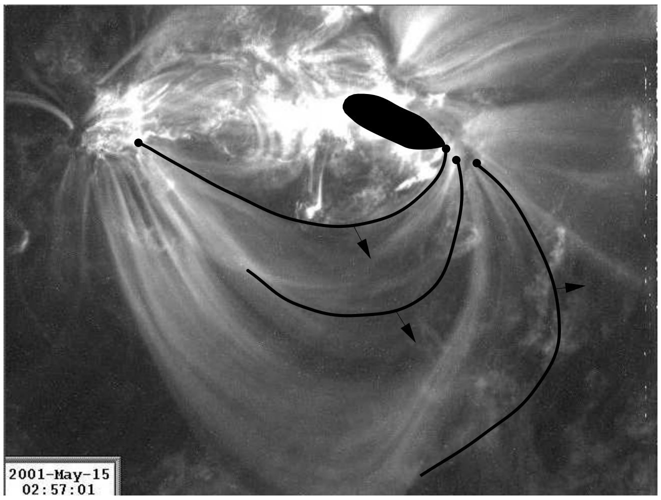

Figure 16. Frame of the movie showing case 16, outlining oscillating loops observed on 15 May 2001, as discussed in Section P.

P. Case 16: 15 May 2001

A flare within the center of an active region excites rapidly damped waves in the higher loops (Fig. 16). The oscillating loops (in the middle of the field of view, as well as loops pointing towards the lower right, i.e., towards the southwest) appear to end at locations where later in the flare some ribbons develop (most clearly on the left-hand side), but also in the spot on the preceding side.

Notice also the peculiar events in the lower right corner: field appear to unwind and lift cool, dark material while twisting into the higher field.

Q. Case 17: 15 June 2001

Associated with a C3.8 flare, the high field appears to open up, without clear signs of a filament ejection. As the field relaxes, damped oscillations are seen in loops of different heights (near A and B in Fig. 17), with clear phase differences between the loops. The most clearly oscillating loops (with a period of approximately 6-7 minutes, at the site of the curve shown in Fig. 17) appear to end at sites that are very bright as a consequence of the explosive event, but identifying those footpoints is difficult, and relies more on the general direction of structures rather than that loops can be traced down to the surface.

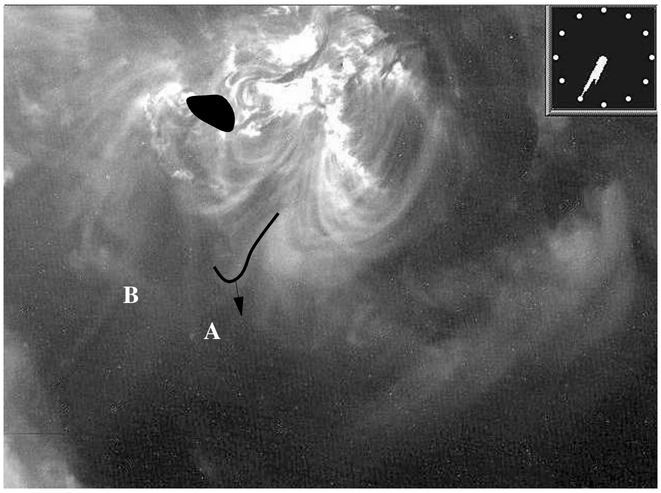

Figure 17. Frame of the movie showing case 17, outlining oscillating loops observed on 15 June 2001, as discussed in Section Q.