Properties of Flares-Generated Seismic Waves on the Sun

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ABSTRACT

The solar seismic waves excited by solar flares ("sunquakes") are observed as circular expanding waves on the Sun's surface. The first sunquake was observed for a flare of July 9, 1996, from the Solar and Heliospheric Observatory (SOHO) space mission. However, when the new solar cycle started in 1997, the observations of solar flares from SOHO did not show the seismic waves, similar to the 1996 event, even for large X-class flares during the solar maximum in 2000-2002. The first evidence of the seismic flare signal in this solar cycle was obtained for the 2003 "Halloween" events, through acoustic "egression power" by Donea and Lindsey. After these several other strong sunquakes have been observed. Here, I present a detailed analysis of the basic properties of the helioseismic waves generated by three solar flares in 2003-2005. For two of these flares, X17 flare of October 28, 2003, and X1.2 flare of January 15, 2005, the helioseismology observations are compared with simultaneous observations of flare X-ray fluxes measured from the RHESSI satellite. These observations show a close association between the flare seismic waves and the hard X-ray source, indicating that high-energy electrons accelerated during the flare impulsive phase produced strong compression waves in the photosphere, causing the sunquake. The results also reveal new physical properties such as strong anisotropy of the seismic waves, the amplitude of which varies significantly with the direction of propagation. The waves travel through surrounding sunspot regions to large distances, up to 120 Mm, without significant decay. These observations open new perspectives for helioseismic diagnostics of flaring active regions on the Sun and for understanding the mechanisms of the energy release and transport in solar flares.

Subject headings: Sun: flares, Sun: helioseismology, Sun: oscillations, sunspots

1.   Introduction

It was suggested long ago (Wolff 1972) that solar flares, giant explosions on the Sun, may cause acoustic waves traveling through the Sun's interior, similar to the seismic waves

on the Earth. Because the sound speed increases with depth the waves are reflected in the deep layers of the Sun and appear back on the surface, forming expanding rings of the surface displacement. Theoretical modeling (Kosovichev & Zharkova 1995) predicted that the speed of the expanding seismic waves increases with distance because the distant waves propagate into the deeper interior where the sound speed is higher. First observations of the seismic waves caused by the X2.6 flare of July 9, 1996 (Kosovichev & Zharkova 1998a), proved these predictions. These observations also showed that the source of the seismic response was a strong shock-like compression wave propagating downwards in the photosphere. This wave was observed immediately after the hard X-ray impulse which produced by high-energy electrons hitting the low atmosphere. This led to a suggestion that the seismic response can be explained in terms of so-called "thick-target" models. In these models, a beam of high-energy is related to heating of the solar chromosphere, resulting in evaporation of the upper chromosphere and a strong compression of the lower chromosphere (e.g. Kostiuk & Pikelner 1975; Livshits et al. 1981; Fisher et al 1985; Kosovichev 1986). This high-pressure compression produces a downward propagating shock wave (Kosovichev 1986) that hits the solar surface and causes sunquakes. This shock observed in SOHO/MDI Dopplergrams as a localized large-amplitude velocity impulse of about 1 km/s or stronger represents the initial hydrodynamic impact resulting in the seismic response. In addition, Kosovichev & Zharkova (1998b) found that the seismic wave was anisotropic, with a significant quadrupole component.

The following observations of solar flares made by the Michelson Doppler Imager (MDI) instrument on the NASA-ESA mission SOHO did not show noticeable sunquake signals even for strong X-class flares. This search was carried out by calculating an "egression" power for high-frequency acoustic waves during the flares (Donea et al. 1999). It became clear that sunquakes are a rather rare phenomenon on the Sun, which occurs only under some special conditions. Surprisingly, seven years later several flares did show strong "egression" signals indicating new potential sunquakes (Donea & Lindsey 2005) (for a list see http://www.maths.monash.edu.au/~adonea). It is interesting to note that the flare of July 9, 1996, was the last strong of the previous solar activity cycle, and the new strong sunquake events are observed in the declining phase of the current activity cycle after the maximum of 2000-2001. It appears that during the rising phase of the solar cycle and during its peak the solar flares are rather a "superficial" coronal phenomenon not affecting much the solar surface and interior. This could happen if the topology of magnetic field of solar active regions which produce flares changes in such a way that the magnetic energy is released at lower altitudes in the declining phase of the solar cycle than in the rising and maximum phase. Here, I present analysis of new observations of the seismic response to solar flares from the SOHO and RHESSI space observatories, which show that the sunquakes were indeed caused

by the hydrodynamic impacts of high-energy electrons accelerated in solar flares confirming the initial result of (Kosovichev & Zharkova 1998a), and determine basic properties of the flare-generated seismic waves by investigating their time-distance characteristics.

2.   Results of analysis of SOHO/MDI and RHESSI data

The MDI instrument on SOHO measures motions of the solar surface through the Doppler shift of a photospheric absorption line Ni I 6768 A. The measurements provide images of the line-of-sight velocity of the Sun's surface every minute with the spatial resolution 2 arcsec per pixel. Examples of the MDI Dopplergrams obtained during the sunquake events are shown in the two right columns in Figure 1 (grey semitransparent images overlaying color images of sunspots). There are several types of motions on the solar surface, which contribute to the MDI signal. The largest contributions of about 500 m/s come from the solar convection and stochastic 5-min oscillations excited by convection (they form the noisy granular-like pattern in Fig.1). The amplitude of the flare-generated seismic waves (ring-like features identified in the middle column of Fig.1) rarely exceeds 100 m/s. Thus, because of the strong stochastic motions in the background, these waves are difficult to detect. However, these waves form an almost circular-shape expanding ring, velocity of which is determined by the sound speed inside the Sun and can be calculated from solar models. This property is used to extract the seismic response signal from the noisy data. Because the waves are close to circular the Dopplergrams can be averaged over a range of the azimuthal angle around central points of the initial flare impact. These centers are identified during the flare impulsive phase as strong localized rapidly varying velocity perturbations of about 1 km/s (light and dark features in left column of Fig.1). The azimuthally averaged Dopplergrams are plotted as time-distance diagrams (right columns of Fig.1; the averaging angular range in the polar coordinates in indicated at the top), in which the seismic wave forms a continuous ridge corresponding the time-distance relation for acoustic propagating through the solar interior. The slope of this ridge is decreasing with distance, meaning that the waves accelerate. This happens because the seismic waves observed at longer distances travel through the deeper interior of the Sun where the sound speed is higher because of higher plasma temperature. Typically, the ring speed changes from 10 km/s to 100 km/s. In the "egression power" method (Donea et al. 1999) the wave signal is integrated along the time-distance ridge, thus giving the total average of the seismic signal power for specific central points. The egression power can be calculated for the whole Dopplergram revealing places of potential sunquakes. This method is useful as a search tool, but it does not provide characteristics of the seismic waves. Because of the high solar noise, the seismic waves are not easily seen on individual Dopplergrams. They are much easier recognized in

Dopplergram movies as expanding circular wave fronts. The typical oscillation frequency of the flare waves is higher than the mean frequency of the background fluctuations (4-5 mHz vs. 3 mHz). Therefore, frequency filtering centered at 5 or 6 mHz helps to increase the signal-to-noise ratio. In most cases, a frequency filter centered at 6 mHz with the width of 2 mHz is used, and, in addition, the difference filter for consecutive images is applied.

Localized Doppler perturbations during the flare impulsive phase, similar to shown in the Fig.1 (left panels) and presumably associated with precipitation of high-energy particles are commonly observed. Therefore, that one might expect that seismic waves are excited in most flares that affect the photosphere. However, in most cases the flare hydrodynamic impact in the photosphere and, thus, the seismic response appear to be weak. The main purpose of this paper is to investigate properties of strong seismic waves when their wave fronts can be observed explicitly in Dopplergrams and time-distance diagrams. A list of 6 flares with such strong seismic waves, observed from SOHO/MDI between 1996 and 2005 in given in Table 1.

Figure 1 presents results for three strongest events so far, observed on 10/28/2003, 07/16/2004 and 01/15/2005. The first flare of October 28, 2003, was one of the strongest ever observed, having the soft X-ray class X17. It is interesting that the two other flares had much weaker soft X-ray class, but produced higher amplitude seismic waves than this one. The analysis of these observations reveals new interesting features of the seismic response: 1) flares can produce multiple sunquakes almost simultaneously originating from separate positions (as also found by Donea & Lindsey (2005) for the 10/28/2003 flare); 2) the seismic waves are highly anisotropic, their amplitude can vary significantly with angle; 3) the strongest amplitude is commonly observed in the same direction as the direction of motion of flare ribbons; 4) the wave fronts in most cases have elliptical shape, originating from elongated in one direction initial impulse; 5) the centers of the expanding waves coincide very well with the places of hydrodynamic impacts in MDI Dopplergrams (confirming the initial observation of Kosovichev & Zharkova 1998a), however, not all impact sources produce strong seismic waves; 6) the seismic waves are usually first observed 15-20 min after the initial impact, and reach the highest amplitude 20-30 min after the flare; 7) the seismic waves can travel to large distances exceeding 120 Mm, but, in some cases, decay more rapidly; 8) the fronts of acoustic seismic waves propagate through sunspots without much distortion and significant decay, thus showing no evidence for conversion into other types of MHD waves; 9) the time-distance diagrams for the waves propagating in sunspot regions show only small deviations of the order of 2-3 min from the wave travel times of the quiet Sun; these variations are consistent with the travel time measurements obtained by time-distance helioseismology using the cross-covariance function for random waves (Duvall et al. 1997; Kosovichev et al. 2000).

For two of these flares, X17 of October 28, 2003, and January 15, 2005, X-ray data are available for analysis. The RHESSI image reconstruction software was used to obtain locations of the X-ray sources in these flares and compare with the MDI Doppler measurements of the hydrodynamic impulses and seismic responses. Figure 2 shows a white-light image of the flaring active region (NOAA 10696) and the superimposed images of the Doppler signal at the impulsive phase, 11:06 UT, (blue and yellow spots show up and down photospheric motions with variations in the MDI signal stronger than 1 km/s), positions of three wave fronts at 11:37 UT, and also locations of the hard X-ray (50-100 keV) sources (yellow circles) at 11:06 UT, and 2.2 MeV gamma-ray sources (green circles) found by Hurford et al. (2004) (averaged for the whole flare duration).

Evidently, the X-ray and gamma-ray source are very close to the positions of the seismic sources, but there was no gamma-ray emission near source 3. Also, the gamma emission was not detected for other seismic events. This leads to the conclusion that the origin of the seismic response is the hydrodynamic impact (shock), which is observed in the Doppler signals at 11:06 UT and shows the best correspondence to the central positions of the wave fronts, contrary to the suggestion of Donea & Lindsey (2005) that photospheric heating by high-energy protons is likely to be a major factor. This was verified by calculating the time-distance diagrams for various central positions and various angular sectors. When the central position of a time-distance diagram deviates from the seismic source position this deviation is immediately seen in the diagram as an off-set of the time-distance ridge. This approach provides effective source positions for complicated and distributed Doppler signals.

The flare of January 15, 2005, of moderate X-ray class, X1.2, but it produced the strongest seismic wave observed so far by SOHO (Fig.1, bottom row). Its amplitude exceeded 100 m/s. This wave had an elliptical shape with the major axis in the SE-NW direction. The elliptical shape corresponds very well to the linear shape of the seismic source extended in this case along the magnetic neutral line. This is illustrated in Figure 3. The left panel shows the grey-scale map the Dopplergram difference at 0:40 UT, in which the long white feature near the center corresponds to strong downflows at the seismic source, and an image of the hard X-ray source (color spot). The right panel shows the corresponding MDI magnetogram and an image of the soft X-ray emission (in gray) and contour line of the hard X-ray source. Evidently, the region of the hydrodynamic impact was located just below the hard X-ray source, which was at a footpoint of the soft X-ray loop. Figure 4 illustrates this sequence of events for the January 15, 2005, flare, from top to bottom.

The high-energy electrons accelerated in the flare (presumably, high in the corona) produced hard X-ray impulse in the lower atmosphere and generated downward propagating shocks which hit the photosphere and generated the seismic waves. This picture corresponds

very well to the standard thick target model of solar flares (Svestka 1970) and the models of the hydrodynamic response (e.g. Kostiuk & Pikelner 1975; Livshits et al. 1981; Fisher et al 1985; Kosovichev 1986). The soft X-ray image indicates this flare was rather compact. One may suggest that the seismic response can be particularly strong in the case of a compact solar flare, but this needs to be confirmed by further observations.

3.   Discussion

The new observations from SOHO and RHESSI provide unique information about the interaction of the high-energy particles accelerated in solar flares with solar plasma and the dynamics of the solar atmosphere during solar flares. These data also provide unique information about the interaction of acoustic MHD waves with sunspots, showing explicitly propagation of wave fronts through sunspot regions. This opens opportunity for developing new methods of helioseismology analysis of flaring active regions, similar to the methods of Earth-quake seismology.

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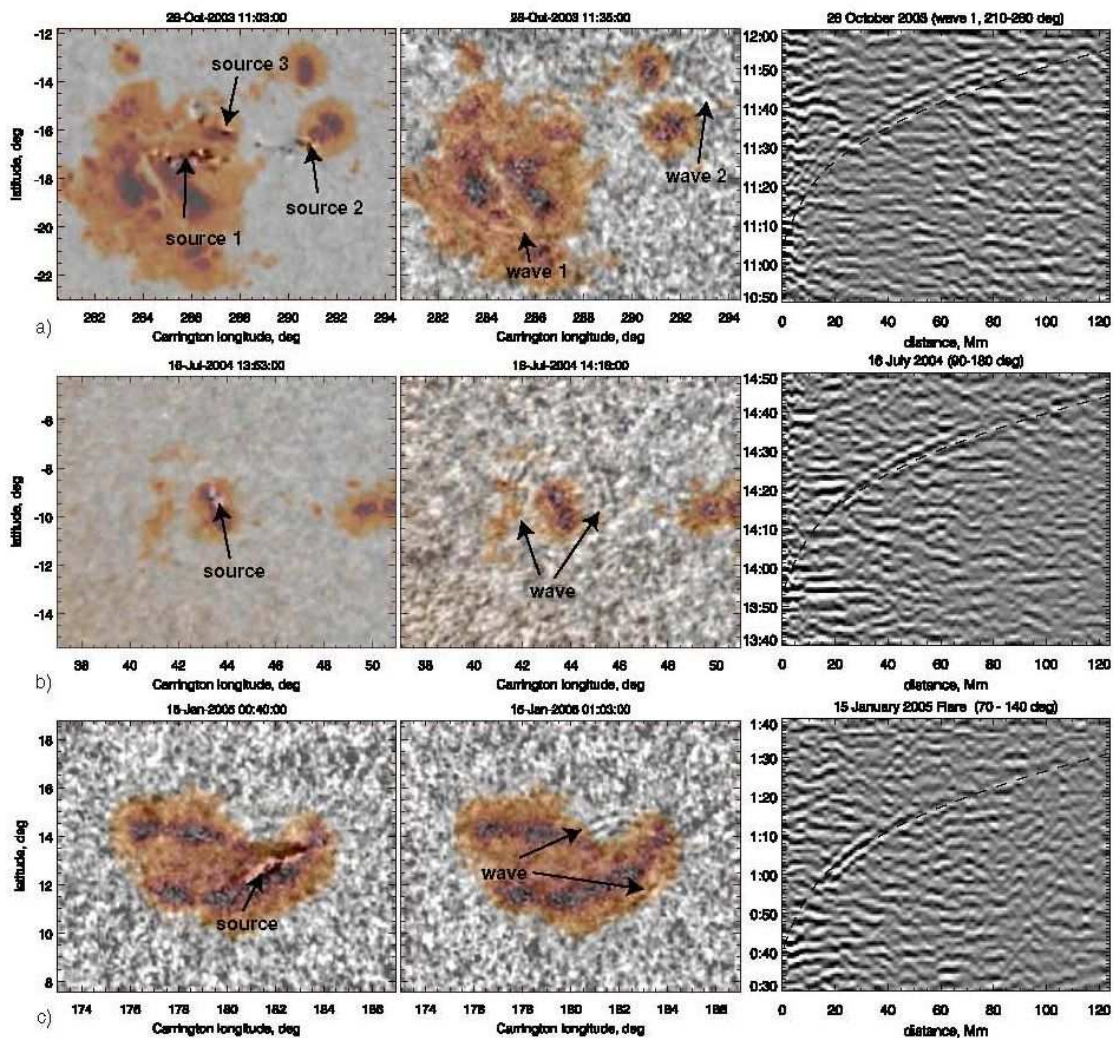Svestka, Z., 1970, Sol. Phys., 13, 471

Fig. 1.— Observations of the seismic response of the Sun ('sunquakes") to three solar flares: X17 of October 28, 2003 (top panels), X3 of July 16, 2004 (middle panels) and X1 flare of January 15, 2005. The left panels show a superposition of MDI white-light images of the active regions and locations of the sources of the seismic waves determined from MDI Dopplergrams, the middle column shows the seismic waves, and the right panels show the time-distance diagrams of these events. The dashed curve is a theoretical time-distance relation for helioseismic waves.
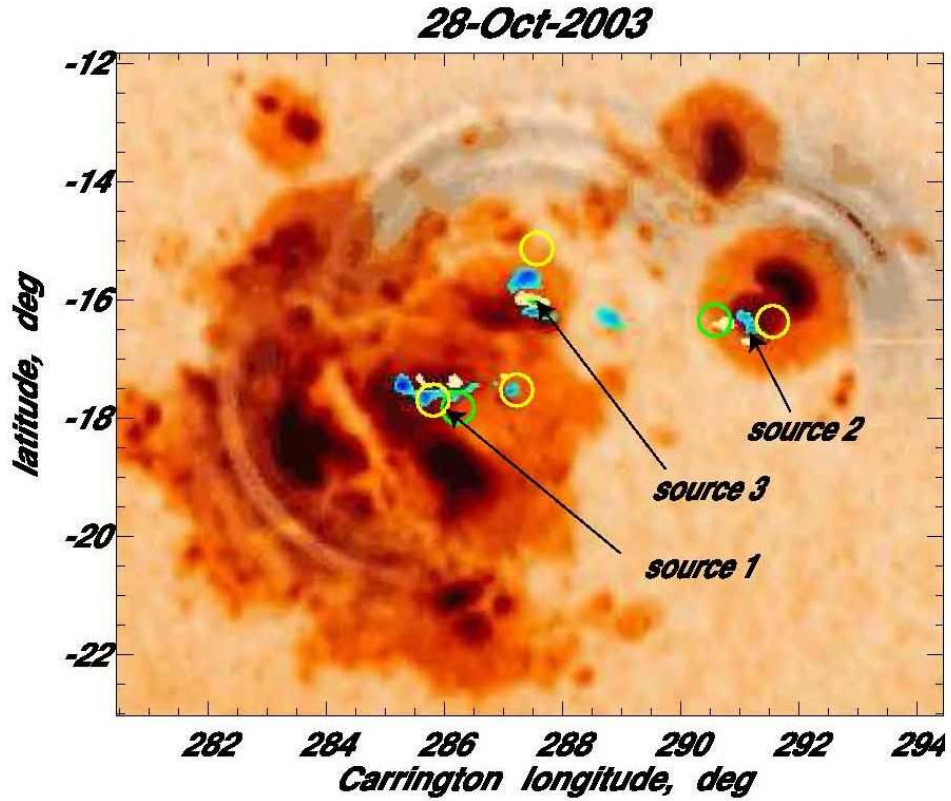
Fig. 2.— . A white-light image of active region NOAA 10696 observed on October 28, 2003, and superimposed images of the Doppler signal at the impulsive phase, 11:06 UT, (blue and yellow spots show up and down photospheric motions with variations in the MDI signal stronger than 1 km/s), positions of three wave fronts at 11:37 UT, and also locations of the hard X-ray (50-100 keV) sources (yellow circles) at 11:06 UT, and 2.2 MeV gamma-ray sources (green circles).
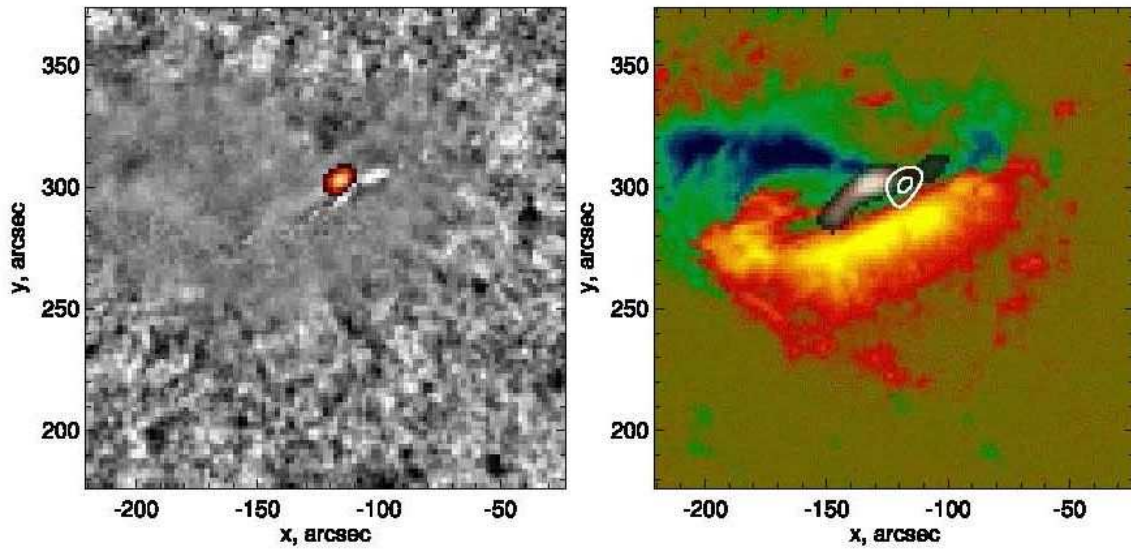
Fig. 3.— Seismic and X-ray sources of the X1.2 flare of January 15, 2005. Left panel shows the Dopplergram difference at 0:40 UT, in which the long white feature near the center corresponds to strong downflows at the seismic source and an image of the hard X-ray source (color spot). The right panel shows the corresponding MDI magnetogram (red-positive magnetic polarity of the line-of-sight component of magnetic field, blue –negative polarity) and an image of the soft X-ray emission (in gray) and contour line of the hard X-ray source.
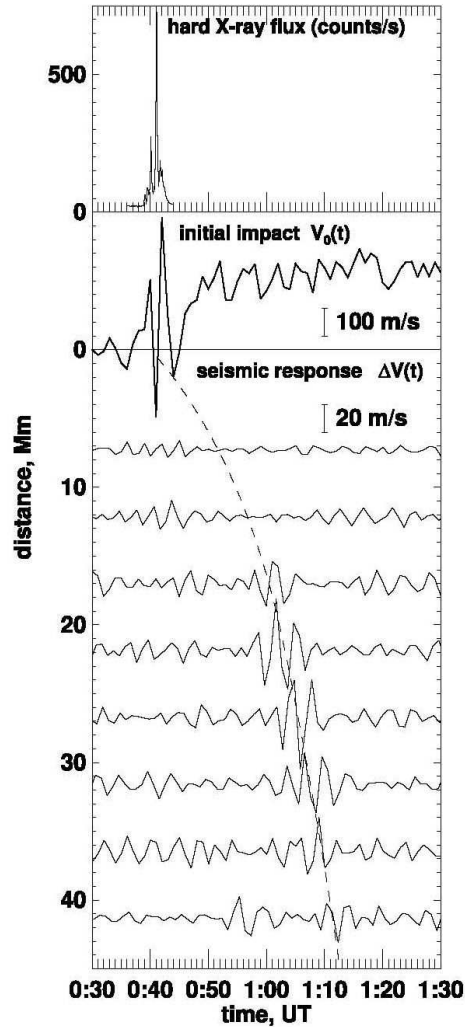
Fig. 4.— . The sequence of events during the flare of Janury 15, 2005. High-energy electrons accelerated in the solar flare and interact with the lower atmosphere, producing hard X-ray emission (observed by RHESS) and shocks – initial hydrodynamic impact in the photosphere (observed by SOHO/MDI). Then, about 20 min after the initial impact an expanding seismic wave was detected by SOHO/MDI. The dashed curve shows a theoretical relation for helioseismic waves.

Table 1: Solar flares with strong sunquake events.

Date	X-class	Start time	Peak time	End time
9 July 1996	X2.6	09:01	09:12	09:49
28 October 2003	X17	09:51	11:10	11:24
29 October 2003	X10	20:37	20:49	21:01
16 July 2004	X3.6	13:49	13:55	14:01
15 August 2004	M9.4	12:34	12:41	12:43
15 January 2005	X1.2	00:22	00:43	01:02