Current State of Seismic Emission Associated with Solar Flares

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Abstract:Certain solar flares are followed by photospheric seismic emission, also known as sunquakes. Sunquakes were predicted more than 40 years ago, but observed for the first time 20 years ago. A valid scenario that would fit all discoveries made so far is still missing. This paper summarises the current state of the literature concerning sunquakes. It describes all published reports of known seismic sources to date and presents possible triggering mechanisms.

Key words: sunquakes, solar flares

1. Introduction

Solar flares represent one of the most energetic phenomena produced by the Sun. Although they have been studied since the detection of a localised brightening in a sunspot group (Carrington, 1859; Hodgson, 1859) and intensely analysed during the space era, they are still a puzzling phenomenon.

Flares occur when magnetic energy is suddenly released (Benz, 2008), energy that has been stored in the solar atmosphere, above an active region. Radiation is emitted across virtually the entire electromagnetic spectrum, from radio waves at the long wavelength end, through optical emission to X-rays and gamma rays at the short wavelength end. Flares are considered to result from the loss of equilibrium in magnetic configurations (Benz, 2008). Their consequences include changing local magnetic configuration and forming shocks that can penetrate to the lower layers of the Sun's atmosphere.

The atmosphere of the Sun is structured in several layers with the outermost one being the corona (optically thin, lowest density), followed by a transition layer, the chromosphere and the photosphere (optically thick, high density). Space observations of plasma velocities and magnetic variability at the photospheric level have facilitated the detection of several periodic oscillations starting with the well-known 5-minutes oscillations (Noyes and Leighton, 1963; Stein and Leibacher, 1974). Long timescale Doppler observations, using for example the Michelson Doppler Imager (MDI) aboard the Solar and Heliospheric Observatory (SoHO) and the terrestrial GONG network, have provided high-resolution l-ν (angular degree versus frequency) diagrams for the first time.

Helioseismology has proven to be one of the most exact astronomical sciences, where theory and observations agree very well, making it an exceptional tool for precisely studying the Sun’s interior based on observed surface data. Over the last two decades the information gathered by SOHO and, later by SDO, has greatly extended our knowledge concerning the sound waves and their propagation inside the Sun. Sunquakes were initially predicted more than 40 years ago (Wolff, 1972), but were observed for the first time twenty years ago (Kosovichev and Zharkova, 1998).

Wolff (1972) was amongst the first to suggest possible stimulation of “high-order modes of solar oscillation to interesting amplitudes”. Haber et al. (1988a) considered possible excitation of acoustic modes within the Sun, but argued that fluctuation in power ridges may be dominated by data noise.

The first attempt at computing radial propagating waves using Doppler velocities interpolated onto a cylindrical coordinate system was performed by Haber et al., (1988b), who suggested that the flare may have excited outgoing waves. Braun and Duvall (1990) presented their results as “unable to detect an excess of oscillatory power in the vicinity of the active region following a large flare”, but did not rule out the existence of sun quakes.

Kosovichev and Zharkova (1998) first identified a sunquake using MDI/SOHO surface velocity data with a factor-of-4 image enhancement technique that revealed expanding rings (Zharkova and Kosovichev, 1998). The term “sunquake” was used to characterise a roughly circular surface ripple observed accelerating outwards from the site of an impulsive X 2.6 flare of July 9, 1996. The ripples were seen 20–60 minutes after the flare's impulsive phase in Dopplergrams using the enhancement factor of 4, though in general identifying surface ripples from flares is problematic, and not a reliable means of detection (Besliu et al., 2005). The ripples are often swamped by the 5-minute oscillations.

Donea et al. (1999) subsequently applied computational seismic holography to the MDI observations of the 1996 flare in order to obtain the "egression power maps" (Lindsey and Braun, 2000). These maps showed a relatively compact seismic source for the flare (July 9, 1996), that was the first X-type flare from Solar Cycle 23. The seismic source appeared centred on a delta–configuration sunspot in the middle of the flaring active region (NOAA 7978), where Kosovichev and Zharkova (1998) had also noted a local transient disturbance in the MDI Doppler maps at the onset of the flare. The seismic source spread over the two oppositely polarized umbrae that formed the heart of the sunspot, roughly extending 15 Mm in the east-west direction and 18 Mm in the north-south direction.

2. Common Detection Methods

2.1 Helioseismic Holography

Generating an acoustic hologram of the solar surface was first introduced by Roddier (1975). The procedure aimed to allow photographic recording of the complex amplitude of photospheric oscillations as a function of the position on the solar disk. Underlying acoustic sources might have been then visualized by observing such a hologram under coherent light.

For imaging acoustic sources generated by solar flares Lindsey and Braun (2000) described a technique named computational helioseismic holography. This technique is used to image acoustic sources on and beneath the Sun's photosphere. It reconstructs phase-coherent p-mode acoustic waves that are observed at the photosphere into the solar interior to render stigmatic images of the subsurface sources that have perturbed this surface.

The solar interior refracts down-going waves back to the surface because of its temperature gradient below the photosphere. Helioseismic holography uses observations in a particular area, to image another area, in a way that is "broadly analogous to how the eye treats electromagnetic radiation at the surface of the cornea, wave-mechanically refocusing radiation from submerged sources to render stigmatic images" (Lindsey and Braun, 2000). In order to obtain these images, holography uses a pupil defined as an annulus with radius 15–45 Mm, to image the focus situated a considerable distance from the pupil.

The main computations in holography are of the "ingression" and "egression". The two quantities are obtained by analysing the acoustic signal in helioseismic observations at the solar surface. These two quantities are estimates of the wave-field in the solar interior; the ingression is an assessment of the observed wave-field converging upon the focal point while the egression is an assessment of waves diverging from that point. The ingression, H_-, and the egression,H_+, are obtained from the wave-field at the surface, ψ, through theoretical Green's functions.

When the surface acoustic field at any point $\boldsymbol{r}$in the pupil is expressed as a complex amplitude $\hat{\psi}$ (which may for example be a velocity or an intensity) for any given frequency ω, the acoustic egression can be expressed as $\hat{H}_+(\boldsymbol{k},\omega)$ whereH_+ is computed based on a Green's function $\hat{G}_+$ that expresses the disturbance at the focus, $\boldsymbol{r}$. A Fourier transform links frequency and time descriptions of the MDI surface acoustic field.

The egression power $P(\boldsymbol{r},t)=|H_+(\boldsymbol{r},t)|^2$ is extensively used in detecting or studying acoustic sources and absorbers. This equation is used when calculating the egression power for each pixel in the image. Therefore, using this technique one can create maps of egression power around active regions with the main aim of detecting seismic sources. This translates into visual detection of signatures in the spatial and temporal neighbourhoods of localized seismic transient emitters.

The helioseismic technique has been applied to Dopplergrams – solar surface Doppler velocities maps – such as those provided by the MDI instrument onboardSoHO or HMI (Helioseismic and Magnetic Imager) onboard SDO (Solar Dynamics Observatory). This technique has led to the discovery of several dozen sunquakes.

2.2 Time-Distance Diagrams

As already mentioned, sunquakes were predicted in 1972 (Wolff, 1972): "A large solar flare releases many orders of magnitude more energy than what is required to stimulate high-order modes of solar oscillations to interesting amplitudes". Wolff states that oscillations with periods larger than 100s and velocity amplitudes larger than 1000 cm/s should be observed.

Kosovichev and Zharkova (1998) constructed seismograms (maps of distances travelled by the wave front) of the solar flare by remapping the MDI Doppler images into polar coordinates centred at the point of the initial velocity impulse, and then applying a Fourier transform with respect to the azimuthal angle (Kosovichev and Zharkova, 1998, see Fig. 1d). A seismogram is the record of an earth tremor made by a seismograph, so their idea was to create an analogous concept for the solar quake to show the corresponding wave movement in the Sun.

Later, Kosovichev (2006) constructed seismograms of some of the events and reported the anisotropy of the waves. Martinez-Oliveros et al. (2007, 2008b) discovered seismic ridges from an even weaker, M6.7, flare.

2.3 Seismic Ripples Detection

For a few seismic signatures the ripple expanding outwards from the source region is visible in the raw Doppler velocity maps. However, as they are usually masked by the general 5-minutes oscillations this wave is rarely seen and only once has been reported as being circular. Such a wave was associated with the first sunquake discovered (Kosovichev and Zharkova, 1998). In the case of the July 9, 1996 X2.6 solar flare, the seismic wave was so powerful that its consequent ripple was even seen in simple running differences of Dopplergrams as circular ridges which began about 18 Mm from the flare site and reached about 120 Mm. This technique is used to image the wave front moving in time on the solar surface. The strong fluctuating motions of the background, the permanent 5-minute oscillations, make the ripple difficult to see in individual

Dopplergrams. Only a few of the reported seismic sources produced visible surface ripples (Kosovichev and Zharkova, 1998; Kosovichev, 2006; Kosovichev and Sekii, 2007; Moradi et al., 2007; Martinez-Oliveros et al., 2007) making the physics of seismic flares even more challenging.

3. Observational Efforts to Image Seismic Sources from Flares

The first report of seismic ripples following a X2.6 flare was published in Nature by Kosovichev and Zharkova (1998). Using seismic holography, Donea et al. (1999) imaged the source of this sunquake. They showed that the best frequency to image the seismic transient is the 6 mHz band because the ambient noise in the 6 mHz band is much lower that at 3-4 mHz and the diffraction limit for 6 mHz waves is finer. Donea and Lindsey (2005) reported two more flares followed by acoustic emission, namely the Halloween flares, October 28 and 29, 2003 (X17.2 and X10-type). For the first time their analyses showed multiple compact acoustic sources generated by one flare. These were associated with the footpoints of coronal magnetic loops – as hard X-ray and white light emission from the MDI/SOHO instrument revealed. Besliu-Ionescu et al. (2005) reported 6 more sunquakes, all driven by X-type solar flares. Donea et al. (2006) marked a new stage in considering seismic emission by reporting on a sunquake following an M-type solar flare, as predicted by Donea et al. (2005). For example, on September 9, 2001 an M9.5-class impulsive (8 minutes) solar flare occurred above the active region NOAA 9608. The source of the related sunquake was seen in the 6 mHz-centred egression power maps. Interestingly, Besliu-Ionescu et al. (2006) reported the strongest seismic emission associated with an X class solar flare (January 15, 2005), produced just above one of the most active regions of solar cycle 23, NOAA 10720. This flare showed a very strong seismic signature that was intensely analysed in Moradi et al. (2007) and Martinez-Oliveros et al. (2008a). Kosovichev (2006) reported seismic ripples for the October 28, 2003 and January 15, 2005 sunquakes and added details on the anisotropy of the seismic waves following the velocity transient. Martinez-Oliveros et al. (2007) reported the first sunquake associated with an even weaker solar flare, of M7.4-class, that was detected on August 14, 2004.

The first sunquake report for a flare belonging to solar cycle 24 was presented by Kosovichev (2011), associated with the first X-type solar flare of this cycle. Alvarado Gomez et al. (2012) studied this seismically active flare, concentrating on the magnetic signature in the source region. A systematic analysis of the statistics and causes of solar quakes, including statistics of seismic sources up until the year 2011, is given by Donea (2011).

Matthews et al. (2012) reported the last sun quake following a flare during solar cycle 23, namely the December 14, 2006 X1.5-class flare. They applied acoustic holography to GONG intensity data and GONG velocity data for time-distance analysis. Although the seismic emission is very weak, this has still been declared a positive signal, being discovered using only GONG data. The extensively studied X1.0 flare of March 29, 2014 indeed was reported to generate a weak seismic emission, from an unusual location, a pore or perhaps a remnant of a piece of penumbra of the main sunspot (Judge et al. 2014).

Sharykin et al. (2015) reported the first seismic emission associated with a weak solar flare – a C7.0-class from February 17, 2013. Although the record for that flare states that a M1.9 - class solar flare occurred, the authors have divided the event into two consequent sub-flares, the first one being of C7.0 magnitude.

Buitrago-Casas et al. (2015) performed a survey searching for possible seismic signatures selecting HESSI studied solar flares (http://hesperia.gsfc.nasa.gov/hessidata/dbase). The highest energy band in which flares were observed is above 50 keV. Thus, from a list of 75 selected flares 18 sunquakes were discovered. The authors found seismic activity associated with a C9.7-class flare, as listed by the GOES X-ray catalogue.

4. Magnetic field variations during seismic emissions

The magnetic field configuration of the active region hosting the seismic source seems to play an important role in sunquake triggering. Besliu et al. (2005) studied the two active regions hosting the 2003 “Halloween Flares”. They observed a 7% decrease in the magnetic energy that was followed by a relaxation stage when the seismically active region recovered to its pre-flare magnetic state about 20 minutes later. They showed that the SOHO/MDI data presented rapid variations of the photospheric magnetic field. In penumbral regions, the magnetic field lines are significantly inclined from the vertical. Schunkeret al. (2005) have shown that magnetic forces in inclined magnetic field are of particular significance for acoustic signatures in penumbral regions. Most of the acoustic signatures detected to date are located in the penumbral region of the flaring active region. Similar variations have been observed by Ambastha, Hagyard, and West (1993), Kosovichev and Zharkova (2001), Sudol and Harvey (2005), Wang et al. (2005), Martinez-Oliveros et al. (2007).

Martinez-Oliveros et al. (2008b) reported permanent changes in the magnetic field region that hosted the seismic source. They estimated the work done by Lorentz force as being twice the energy needed for the seismic source. Alvarado-Gomez et al. (2012) studied the seismically active flare of February 15, 2011 from the point of view of energies involved. They also estimated the work done by the Lorentz force, obtaining ~6% of the total energy in the acoustic transient. They do, however warn about the problem related to having only line-of-sight magnetic data, and conclude that the computations should be regarded as underestimates of the real work.

Table 1: List of the events used in the regression model. In bold are shown the events used for validation.

Date	Flare-Type	AR	Position	Ha class	AR-type	Flare times		
SC23								
1996_07_09	X2.6	7978	S10W30	1B	βγδ	09:01	09:12	09:49
2000_06_06	X2.3	9026	N21E10	3B	βγδ	14:58	15:25	15:40
2000_11_24	X2.0	9236	N21W07	SF	β	04:55	05:02	05:08
2001_03_10	M6.7	9368	N27W42	1B	βγ	04:00	04:05	04:07
2001_04_06	X5.6	9415	S21E31	SF	βγ	19:10	19:21	19:31
2001_04_10	X2.3	9415	S23W09	3B	βγδ	05:06	05:26	05:42
2001_09_09	M9.5	9608	S31E26	2N	βγ	20:40	20:45	20:48
2001_09_24	X2.6	9632	S16E23	2B	βγδ	09:32	10:38	11:09
2002_07_15	X3.0	10030	N19W01	3B	βγδ	19:59	20:08	20:14
2002_07_23	X4.8	10039	S13E72	2B	β	00:18	00:35	00:47
2002_08_21	X1.0	10069	S12W51	1B	βγδ	05:28	05:34	05:36
2003_10_23	X5.4	10486	S21E88	1B	βγδ	08:19	08:35	08:49
2003_10_28	X17.2	10486	S16E08	4B	βγδ	09:51	11:10	11:24
2003_10_29	X10.0	10486	S15W02	2B	βγδ	20:37	20:49	21:01
2004_07_16	X3.6	10649	S10E35	3B	βγδ	13:49	13:55	14:01
2004_08_13	X1.0	10656	S13W23	1N	βγδ	18:07	18:12	18:15
2004_08_14	M7.5	10656	S13W29	2N	βγδ	05:36	05:44	05:52
2004_08_15	M9.4	10656	S13W46	1N	βγδ	12:34	12:41	12:43
2005_01_15	X1.2	10720	N14E08	SF	βδ	00:22	00:43	01:02
2005_09_13	X1.5	10808	S11E03	2B	βγδ	19:19	19:27	20:57
2005_12_02	M7.8	10826	S03E14	1N	βγδ	10:05	10:12	10:25
2006_12_14	X1.5	10930	S06W46	2B	βγδ	21:07	22:15	22:26
SC24								
2011_02_15	X 2.2	11158	S21W28	SF	βγ	01:44	01:56	02:06
2011_07_30	M9.3	11261	N16E19		βγδ	02:04	02:09	02:12
2011_09_26	M4.0	11302	N12E22		βγδ	05:06	05:08	05:13
2012_03_09	M6.3	11429	N17W13		βγδ	03:22	03:53	04:18
2012_05_10	M5.7	11476	N12E22		βγδ	04:11	04:18	04:23
2012_07_04	M5.3	11515	S20W18	1B	βγδ	09:47	09:55	09:57
2012_07_05	M4.7	11515	S17W37		βγδ	03:23	03:36	03:39
2012_07_05	M6.2	11515	S20W32	1B	βγδ	11:39	11:44	11:49
2012_07_06	M2.9	11515	S18W41		βγδ	01:37	01:40	01:42
2012_10_23	X1.8	11598	S10E42		βγ	03:13	03:17	03:21
2013_02_17	M1.9	11675	N12E22		β	15:45	15:50	15:52
2013_07_08	C9.7	11785	S07W03		βγδ	01:13	01:22	01:23
2013_11_06	M3.8	11890	S13E36		βγδ	13:39	13:46	13:53
2013_11_07	M2.3	11890	S14E28		βγδ	03:34	03:40	03:43
	M2.4	11890	S14E23	2S	βγδ	14:15	14:25	14:31
2014_01_07	M7.2	11944	S13E11		βγδ	10:07	10:13	10:37
2014_02_02	M2.6	11968	N12E18		βγ	06:24	06:34	06:37

2014_02_07	M1.9	11968	N09W53		βγ	10:25	10:29	10:31

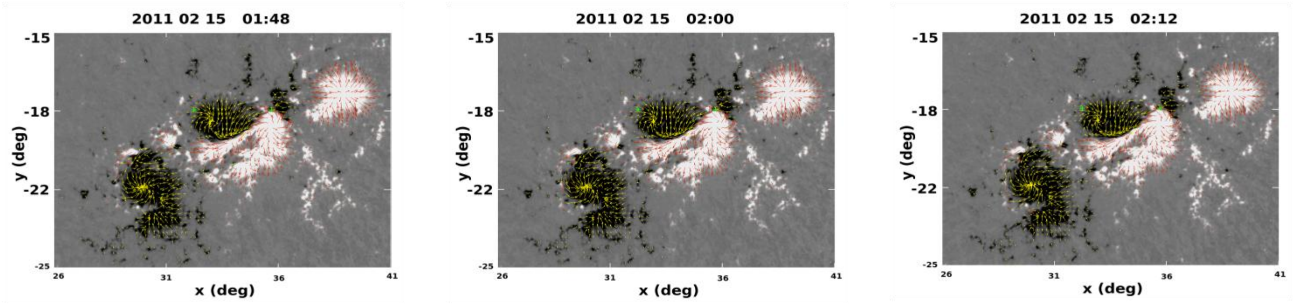

Figure 1: 3D vector magnetograms obtained using SDO/HMI magnetograms. Software courtesy of GherardoValori, 4th Solarnet summer school, MSSL, UK

We present in Figure 1 a succession of three reconstructed vector magnetograms showing the evolution of the magnetic field during the February 15, 2011 solar flare. The locations of the seismic sources as seen in Alvarado-Gomez et al. (2012) are over-plotted in green.

We performed a superposed epoch analysis (e.g. Guo et al. 2011) for all solar flares that had a sunquake associated, considering the maximum flare time defined by Rhessi (http://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_list.txt) as t=0. Some of the events were excluded due to data gaps (August 21, 2002, Dec 2, 2005), either because of multiple Rhessi flares during the selected time interval or unmatched peak times.

We separated the events based on affiliation to the solar cycles. This showed that the profiles corresponding to flares belonging to SC23 were nosier starting with energies above 25 keV. In this case, during the selected interval, there were usually more similar flares and therefore, the different maxima from Figure 2 do not show time delays between maximum emission at various energies, but rather the existence of other flares. However, both panels show time delays within two minutes between the maximum emission at lower energies, compared to the maximum emission at higher energies, confirming that highest energy particles are the first to be registered by the instrument.

4. Summary and Discussion

The scope of this review is to generate a recent list of detected seismic events, of Solar Cycles 23 and 24, and to summarize possible mechanisms of a seismic driver. Figure 3 shows the acoustically active flares during the two solar cycles. Between 1997 and 2000, the coverage of the solar flares by the SOHO/MDI instrument was not very good, SOHO missing many flares.

We will summarize the main mechanisms that are suggested for generation of seismic sources from solar flares, from a chronological point of view.

Kosoviochev and Zharkova (1998) predicted a strong downward propagating shock following a high-energy electron beam heating the cool chromospheric ‘target’. The impact of this shock and condensation resulting from explosive ablation of the chromosphere and propagating downwards through the photosphere, would be the cause of the seismic response.

Donea and Lindsey (2005) stated that there is a direct link between energetic particles accelerated during the flare and acoustic waves at the footpoints of the loop, as a hydrodynamic response of the chromosphere or possibly the underlying photosphere to these particles. They also show evidence of high-energy protons impinging onto the chromosphere in the vicinity of the detected acoustic sources. Using observations of emission in the D_1 line of neutral sodium at the onset of the October 29, 2003 flare, they show evidence of downward-propagating shock/condensation at the onset of the flare. They conclude that photospheric heating by high-energy protons is a major factor in seismic emission.

Besliu-Ionescu et al. (2005) reported that sunquakes are not related to protonic events, stating that there exists evidence that they are driven by impulsive heating at the onset of the flare and evidence of strong downward-propagating shocks and condensations in the chromosphere overlying the compact acoustic source.

Donea et al. (2006) showed that the close spatial correspondence between white-light and acoustic emission supports the hypothesis that the acoustic emission is driven by heating of the lower photosphere. They also mention the strong association between the acoustic source and co-spatial continuum emission, which can be regarded as evidence supporting the back-warming hypothesis. The seismic source coincident with strong, sudden radiative emission in the visible continuum spectrum is an indicator that the photosphere was heated sufficiently to contribute significantly to the observed continuum emission.

Kosovichev (2006) stated that solar flares can produce multiple sunquakes almost simultaneously originating from separate positions, a fact that was also shown by Donea& Lindsey (2005) for the October 29, 2003 flares. He states that the seismic waves are highly anisotropic, and their amplitude can vary significantly with angle. He also remarks on the direction of the strongest amplitude as being in the same direction as the motion of flare ribbons. Kosovichev (2006) also remarks that not all impact sources produce strong seismic waves.

Cally (2006) derived dispersion relations for MHD waves that took into consideration gravitation, magnetic field and acoustic signal. The goal of this paper was to determine the behaviour of acoustic rays when entering regions with strong magnetic field. By

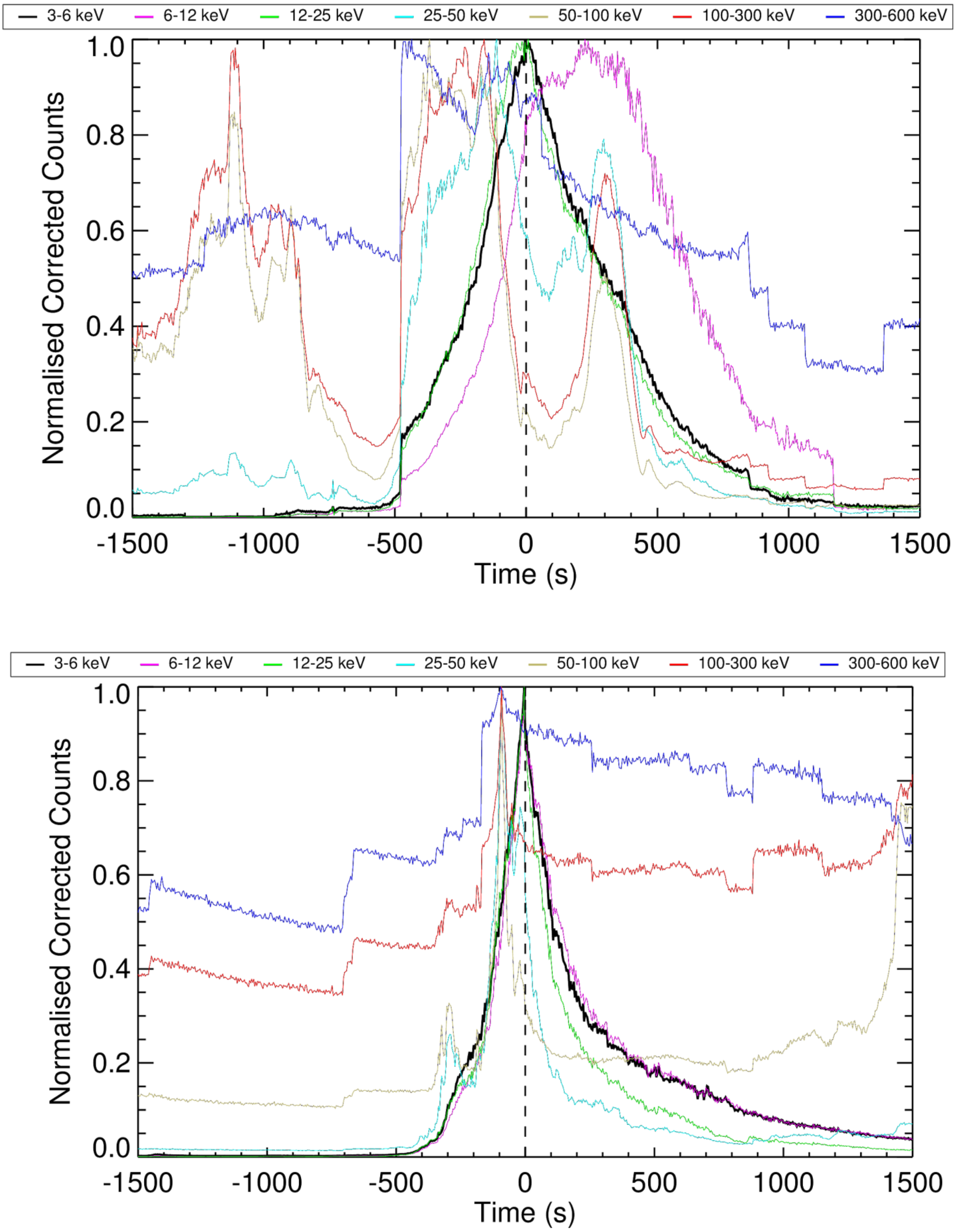

Figure 2: Superposed epoch analysis for Rhessi corrected counts for the seismically active solar flares.
Upper panel – flares from solar cycle 23. Lower panel – flares from solar cycle 24.

2006 it was clear that the sunquakes are related to such regions, all of the sunquakes reported by then being located in the penumbra of the active region hosting the flare. Cally (2006) shows and calculates the fast-to-slow or slow-to-fast conversion that are fundamental aspects of wave behaviour in active regions.

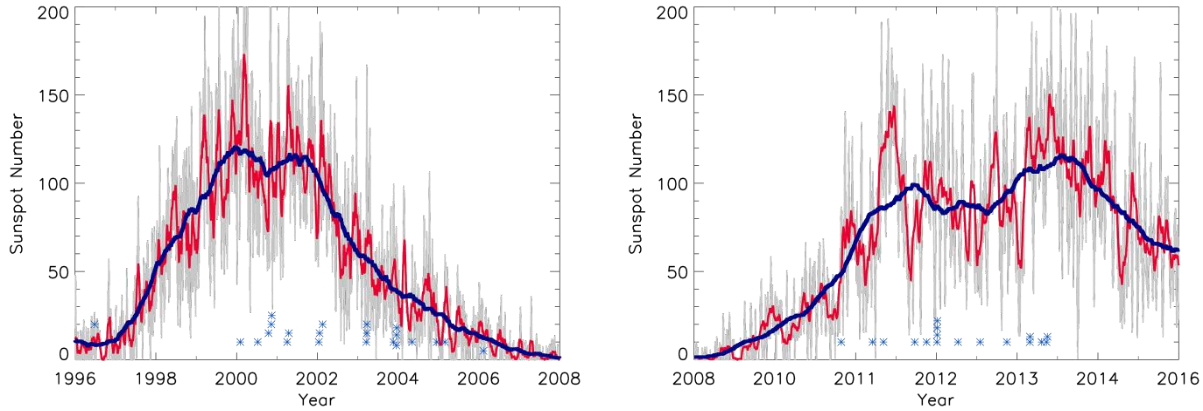

Figure 3: Sunquakes occurrence during solar cycles 23 and 24 (crosses). The grey, red and blue lines represent the daily, monthly, respectively yearly, smoothed sunspot number

Moradi et al. (2007) proposed a mechanism based on the coincidence between the locations of sudden white-light and seismic emission in all analysed acoustically active flares. This would suggest that a substantial component of the seismic emission seen is a result of sudden heating of the low photosphere, associated with the observed excess of visible continuum emission (radiative back-warming). They commented that the origin of white-light emission would have to be entirely in the chromosphere where energetic electrons dissipate their energy, mainly by ionizing previously neutral chromospheric hydrogen down to the depth of the temperature minimum. Donea& Lindsey (2005), Donea et al. (2006) and Moradi et al. (2007) analysed this particular process in detail. They cite Chen & Ding (2006) to support the idea that the white-light flare signatures highlight the importance of radiative backwarming in transporting the energy to the low photosphere, when direct heating by beam electrons is impossible.

Another possible mechanism was proposed by Zharkova &Zharkov (2007) who suggest that high-energy protons, can directly deposit energy in the photosphere, inducing a seismic source. However, for the flare of January 15, 2005, there is no indication of high-energy protons that could directly supply the energy as stated by Martinez-Oliveros et al. (2008a).

Martinez-Oliveros et al. (2008a) confirm the hypothesis considered by Donea& Lindsey (2005) and Kosovichev (2006), that the photospheric emission is a direct continuation of chromospheric shocks. For the flare they study, the hydrodynamic impact of the photosphere was clearly significant since, this X1.2 type flare triggered a very powerful seismic source and visible seismic waves. They also state that the spatial coincidence between the HXR emission and the seismic source connect the two processes, and conclude that the high-energy electrons played an important role. They analysed the statistics of acoustically active events (Besliu-Ionescu et al. 2012) and acknowledged that most solar flares do not produce sunquakes. They concluded that for the majority of flares, strong radiative damping depletes the chromospheric transient before its arrival at the low photosphere. They also show that energetic electrons consistent with HXR signatures are insufficient to account for the direct heating needed by the seismic source.

Zharkova (2008) studied five sunquakes from the observational point of view and discussed several theoretical aspects of the mechanisms implied in their triggering. The paper summarises particle kinetics and plasma dynamics of processes leading to sunquakes. This was an extensive work explaining phenomena such as: particle acceleration during flares – could explain why hard X-ray emission is not usually accompanied by γ rays, or they are spatially and temporally separated –; magnetic field changes – Lorentz-force transients can result from reconnection, a result proposed by Kosovichev and Zharkova (2001); particle precipitation – adding particle-wave interaction to collisions and Ohmic dissipation; plasma heating by electrons and protons – studying how different particle beams can deposit their energy, concluding that softer and weaker beams will deposit their energy mainly in the corona, while harder and more powerful beams will reach deeper into the chromosphere. Considering the response of the atmosphere after the flare, Zharkova (2008) proposes that the moderate intensity harder electron beams could produce shocks to cause seismic emission such as reported by Donea et al. (2006) and Martinez-Oliveros et al. (2008b). Discussing back-warming Zharkova (2008) states that it cannot account for the momentum delivered to the photosphere as pointed out by Donea et al. (2006). Zharkova (2008) concludes that seismic emission triggered by M-class solar flares is related to such flares that have hard proton spectra in hard X-rays.

Fletcher and Hudson (2008) propose an alternative mechanism of energy transport to the “thick-target” model: the energy can be transported by the Poynting flux of Alfvén waves. They studied the energy transport during flares by Alfvén waves. Inspired by this type of transfer occurring for terrestrial aurora, they apply similar ideas to the solar atmosphere. This mechanism that is well established for Earth's magnetosphere, could account for short transport times such that they can explain X-ray source time variations and tight conjugacy. Based on microwave observations they compute Alfvén wave speeds that are above 10^4 km/s. Fletcher and Hudson (2008) propose that after the magnetic reconfiguration of the coronal magnetic field large-scale Alfvén wave are produced among other types of wave pulses. They conclude that an Alfvén wave Poynting flux can accelerate particles in the chromosphere or at the base of the coronal loop.

Hudson et al. (2008) suggested that the “McClymont magnetic jerk” (a rapid dynamical rearrangement of magnetic field after reconnection) could account for the seismic activity of some flares. This hypothesis was used to explain the formation of the acoustic kernel, but could not explain the diffuse lenticular element of seismic activity, surrounding the main kernel of the January 15, 2005 seismic source.

Petrie and Sudol (2010) studied the changes in longitudinal photographic magnetic field during flares away from the solar limb. They reinforce the hypothesis of Hudson et al. (2008), concerning the photographic magnetic fields that become more tilted during flares, that this effect is important in generating sunquakes.

Zharkov et al. (2011) proposed that the sunquake of the 2011 February 15 X-class solar flare was triggered at the footpoints of the erupting flux rope at the start of the flare impulsive phase. This work shows the main HXR sources appearing later at the footpoints of the flare loops formed under the rising flux rope. This is an interesting scenario which requires a few more examples of this nature to be able to solidify a model of erupting flux ropes as a cause of quakes. More implications of this new scenario for the theoretical interpretation of the forces driving sunquakes are discussed in the paper.

Donea (2011) has reviewed the status of the knowledge related to sunquakes and lists four possible mechanisms of sunquake generation: chromospheric shocks (Kosovichev and Zharkova, 1998), impulsive heating of the low photosphere (Donea et al., 2006), direct interaction of high-energy protons with the photosphere (Donea and Lindsey 2005, Zharkova and Zharkov, 2007) and the “McClymmont Jerk” (Hudson et al.,2008). Donea (2011) concludes that the forward modelling supports the radiative back-warming, but that changes in the magnetic field configuration could also trigger seismic emission.

Based on vector magnetograms Fisher et al. (2012) compute the change in Lorentz force that occur during large solar flares and support the idea that these transients can lead to sunquakes.

Sharykin et al. (2015) showed a close association of the flare energy release with a rapid increase in the electric currents and suggested that the sunquake initiation is unlikely to be caused by the impact of high-energy electrons. It may instead be associated with rapid current dissipation or a localized impulsive Lorentz force in the lower layers of the solar atmosphere.

Unfortunately, their work is based on vector magnetograms taken every 12 minutes, whereas the photospheric seismic response to a flare happens in a much shorter period of time. In the future, a high cadence time series will clearly reveal the temporal link between the flare elements.

The exact physical mechanisms that trigger a seismic emission remains, still, under debate.

This work has summarized the increased interest in flare seismology in recent years. We have not covered the topic of the numerical modelling of sunquakes and the chromosphere and photospheric responses to flares. High resolution telescopes such as NST (Big Bear Observatory, Jing et al., 2016) and Daniel K Inouye Solar Telescope (DKIST) will be able to reveal more about the solar location of seismic sources. With a four-metre diameter primary mirror, the DKIST will be able to pick up unprecedented detail on the morphology of seismic sources. A refining of the helioseismic holography method combined with the new high resolution data advance our understanding of the frequency dependent kernelisation of seismic sources. Whether the kernel structure seen in seismic sources is due to interference patterns in the optical method, or is a feature of the seismic source itself, may be revealed after 2019, when DKIST will become operational.

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References

Alvarado-Gomez, J.D., Buitrago-Casas, J.C., Martinez-Oliveros, J.C., Lindsey, C., Hudson, H., Calvo-Mozo, B.: 2012, Sol. Phys. 280, 335.

Ambastha, A., Hagyard, M.J., West, E.A.: 1993, Sol. Phys. 148, 277.

Benz, A.O.: 2008, Living Reviews in Solar Physics 5, 1.

Besliu, D., Donea, A.-C., Cally, P., Maris, G.: 2005, Romanian Astron. J. 15, 33.

Besliu-Ionescu, D., Donea, A.-C.,Cally, P., Lindsey, C.: 2005, inD. Danesy, S. Poedts, A. De Groof and J. Andries (eds.)The Dynamic Sun: Challenges for Theory and Observations, ESA SP-600. Publ. on CDROM., id.111.1.

Besliu-Ionescu, D., Donea, A.-C., Cally, P., Lindsey, C.: 2006, Romanian Astron. J. Suppl. 16, 203.

Besliu-Ionescu, D., Donea, A.-C., Cally, P., Lindsey, C.: 2012, Advances in Solar and Solar-Terrestrial Physics, G. Maris, C. Demetrescu (eds.), Research Signpost, Kerala, India, p. 31.

Braun, D.C. & Duvall, T.L., Jr.: 1990, Sol. Phys. 129, 83.

Buitrago-Casas, J.C., Martinez Oliveros, J.C., Lindsey, C., Calvo-Mozo, B., Krucker, S., Glesener, L., Zharkov, S.: 2015, Sol. Phys. 290, 11, 3151.

Cally, P.S.: 2006, Philos. T. Roy.Soc. 364, 333.

Carrington, R.C.: 1859, Mon. Not.R. Astron. Soc. 20, 13.

Chen Q. R., Ding M. D.: 2006, Astrophys. J. 641, 1217.

Donea, A.-C., Braun, D.C., Lindsey, C.: 1999, Astrophys. J. 513, 2, L143.

Donea, A.-C., Lindsey, C.: 2005, Astrophys. J. 630, 2, 1168.

Donea, A.-C., Besliu-Ionescu, D., Cally, P.S., Lindsey, C., Zharkova, V.V.: 2006, Sol. Phys. 239, 1-2, 113

Donea, A.-C.: 2011, Space Sci. Rev. 158, 451.

Fisher, G. H.,Bercik, D. J., Welsch, B. T., Hudson, H. S.: 2012, Sol. Phys. 277, 59.

Fletcher, L., Hudson, H.S.: 2008, Astropys. J. 675, 1645.

Guo, J., Feng, X., Emery, B. A., Zhang, J., Xiang, C., Shen, F., and Song, W.: 2011, J. Geophys. Res. 116, A05106.

Haber, D.A., Toomre, J., Hill, F.: 1988a, in J. Christensen-Dalsgaard and S. Frandsen (eds.)Advances in Helio- and Asteroseismology, Dordrecht, D. Reidel Publishing Co., p. 59.

Haber, D.A., Toomre, J., Hill, F., Gough, D.O.: 1988b, in Domingo, V., and Rolfe, E.J. (eds.). Seismology of the Sun and Sun-Like Stars, ESA-SP-286,p. 301.

Hodgson, R.: 1859, Mon. Not. R. Astron. Soc. 20, 15.

Hudson, H.S., Fisher, G.H., Welsch, B.T.: 2008, in R. Howe, R. W. Komm, K. S. Balasubramaniam and G. J. D. Petrie (eds.), Subsurface and Atmospheric Influences on Solar Activity, ASP Conference Series 383,p. 221.

Jing, J., Xu, Y., Cao, W., Liu, C., Gary, D., Wang, H.: 2016, Nat. Sci. Rep. 6, ID.24319.

Judge, P.G., Kleint, L., Donea, A., SainzDalda, A., Fletcher, L.: 2014, Astrophys. J. 796, 2, 13.

Kosovichev, A.G. and Zharkova, V.V.: 1998, Nature, 393, 6683, 317.

Kosovichev, A.G. and Zharkova, V.V.: 2001, Astrophys J. 550, 1, L105.

Kosovichev, A.G.: 2006, in J. Leibacher, R. F. Stein, and H. Uitenbroek (eds.),Solar MHD Theory and Observations: A High Spatial Resolution Perspective, ASP Conference Series 354, p. 154.

Kosovichev, A.G, Sekii, T.: 2007, Astrophys. J. 670, L147.

Kosovichev, A.G.: 2011, Astrophys. J. Let.734, L15.

Lindsey, C., Braun, D. C.: 2000, Sol. Phys. 192, 1/2, 261.

Martinez-Oliveros, J.C., Moradi, H., Besliu-Ionescu, D., Donea, A.-C., Cally, P.S., Lindsey, C.: 2007, Sol. Phys., 245, 1, 121.

Martinez-Oliveros, J.C., Donea, A.-C., Cally, P.S., Moradi, H.: 2008a, Mon. Not..R. Astron. Soc. 389, 1905.

Martinez-Oliveros, J.C., Moradi, H., Donea, A.-C.: 2008b, Sol. Phys. 251, 613.

Matthews, S., Zharkov, S., Zharkova, V.: 2012, in T. Sekii, T. Watanabe, and T. Sakurai (eds.), Hinode-3: The 3rd Hinode Science Meeting, ASP Conference Series 454, p. 277.

Moradi, H., Donea, A.-C., Lindsey, C., Besliu-Ionescu, D., Cally, P.S.: 2007, Mon. Not.R. Astron. Soc. 374, 3, 1155.

Noyes, R.W., Leighton, R.B.: 1963, Astrophys. J. 138, 631.

Petrie, G.J.D., Sudol, J.J.: 2010, Astrophys. J. 724, 1218.

Roddier, H.: 1975, C.R., Acad. Sci. II B 281, 4, 93.

Shakyrin, I.N, Kosovichev, A.G., Zimovets, I.V.: 2015, Astrophys. J. 807, ID102.

Stein, R.F., Leibacher, J.: 1974, Annual.Rev.Astron.Astr.12, 407.

Schunker, H., Braun, D.C., Cally, P.S., Lindsey, C.: 2005, Astrophys. J. 621, 2, L149

Sudol, J.J. and Harvey, J.W.: 2005, Astrophys. J. 635, 1, 647.

Wang, H., Liu, C., Deng, Y., Zhang, H.: 2005, Astrophys. J. 627, 1031.

Wolff, C.L.: 1972, Astrophys. J. 176, 833.

Zharkov, S., Green, L.M., Matthews, S.A., Zharkova, V.V.: 2011, Astrophys. J. Let.741, L35.

Zharkova, V.V.: 2008, Sol. Phys. 251, 641.

Zharkova, V. V., Kosovichev, A. G.: 1998, in S.G.,Korzennik, A.,Wilson (eds.), Structure and Dynamics of the Interior of the Sun and Sun-like Stars, SOHO 6/GONG 98 Workshop, ESA-SP-418,p. 66.

Zharkova, V.V., Zharkov, S.I.: 2007, Astrophys. Journal,.664, 1, 573.