Space Sci Rev (2011) 158:451–469
DOI 10.1007/s11214-011-9787-7

Seismic Transients from Flares in Solar Cycle 23

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Received: 31 May 2010 / Accepted: 12 May 2011 / Published online: 8 June 2011

Abstract Some solar flares are known to drive seismic waves into the sub-photospheres of the magnetic regions that host them. Sunquakes, which are identified as a wave-packet of ripples are observed on the solar surface emanating from a focal region, known as seismic source or sometimes as a transient. Not all seismic transients from flares generate sunquakes. How these are produced is still a puzzle. In this paper, I will give an overview of the observed properties of sunquakes and efforts to understanding physics underlying them, including numerical modelling of flare-driven oscillations.

Keywords Solar flares · Sunquakes · Local helioseismology · White Light · Back-warming

1 Introduction

Four prospective sources of acoustic waves in the Sun have been significantly considered since the advent of helioseismology: (1) convection (Goldreich and Keeley 1997a), (2) over-stable oscillations (Ando and Osaki 1975; Goldreich and Keeley 1997b), (3) comets occasionally plunging into the Sun (Gough 1994; Kosovichev and Zharkova 1995), and (4) flares (Wolff 1972; Kosovichev and Zharkova 1995). Of these, flares are the only source of acoustic emission that appears to be generated in plain view in the Sun's outer atmosphere. Solar flares are easily seen in the electromagnetic spectrum above the photosphere offering a wide range of energetic information. Flares are a critical part of solar variability at large on a time scale of seconds to hours, the same general time scale as that of seismic waves themselves. Seismic emission from solar flares is especially interesting by its analogy to earth quakes. Just as geologists study the Earth's interior using seismic waves after an earthquake, solar physicists use the photospheric oscillations to probe the interior of the Sun. Sunquakes associated with solar flares, then, open the prospect of using seismology to study the interior structure and dynamics of active-region subphotospheres (Lindsey and Donea 2008).

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The discovery of large starquakes, such as those resulting in the observed X-ray oscillations from the magnetar SGR 1806-20 (Israel et al. 2005), has added urgency to our quest to understand sunquakes as templates maybe, for the stellar case. I will discuss the physics of solar flares as significant generators of seismic waves.

It was suggested in 1972 that solar flares could excite free global oscillations in the Sun in the same way large earthquakes excite free global oscillation in the Earth (Wolff 1972). Kosovichev and Zharkova (1998) discovered the first known instance of seismic emission, from the X2 flare of 1996 July 9 in AR7978, using data from the Michelson-Doppler Imager (MDI) on board of Solar Heliospheric Observatory (SOHO). They identified the phenomenon by the name "sunquake." Sunquakes are a manifestation of a considerable flux of acoustic energy, $\sim 4 \times 10^{20}$ J (4×10^{27} erg), injected into the solar interior (Donea et al. 1999) by a flare. The manifestation of this acoustic energy is seen 20–50 Mm from the source when it refracts back to the solar surface within about an hour after the commencement of the flare. This refraction is a result of the increasing sound speed with increasing depth in the solar interior. The major surface manifestation is a wave-packet of ripples seen in Doppler maps accelerating outward from the general source region. The horizontal speed of the waves increases from 30 km/s at a distance of 20 Mm from the epicenter of the sunquake to 100 km/s (at a distance of 120 Mm). The amplitude of the Doppler velocity was $\sim$50 km/s (Kosovichev and Zharkova 1998).

We have habitually characterized flares accompanied by sunquakes that are significantly conspicuous by some appropriate diagnostic as "acoustically active." Flares that show no such significant sunquakes are characterized as "acoustically inactive," relatively speaking, or more concisely, "quiet," the qualification "acoustically quiet" seeming slightly redundant. Studies of sunquakes, supported by extensive space-borne and ground-based observations, have shown a number of distinctive qualities of flare acoustic emission:

- Sunquakes are unusual. Most flares, even large ones, do not generate detectable seismic emission in the p-mode spectrum.
- Of the few flares that do, the acoustic energy released is only a small fraction of the radiative energy released.
- Acoustically active flares are the most compact acoustic sources known.
- Flare acoustic emission is the hardest acoustic radiation known so far, i.e. the most relatively intense at high frequencies (Besliu-Ionescu 2010).
- Sunquakes seem to be generated by impulsive white-light flares.[1]
- Flares have been known to produce multiple seismic transients at the photosphere almost simultaneously.
- While protonic flares frequently produce sunquakes, there are instances of non-protonic flares that produced strong sunquakes.
- The magnetic configurations of active regions undergo significant changes during a sunquake, suggesting that Lorentz forces play a significant role in flare acoustic emission.

Despite the large amount of observational data collected for flares with sunquakes from all over the electromagnetic spectrum, the generation of seismic transients is, as yet, poorly understood. We think we have a fairly clear picture of how flares are manifested in the chromosphere. High-energy non-thermal electrons, and in some instances protons, accelerated during flares impinge into the chromosphere heating the formerly thermal plasma. When

[1] All acoustically active flares discovered to date have been white-light flares when the latter could be confirmed. However, there have been significant instances of acoustically inactive white-light flares.

the non-thermal electron flux is sufficiently large that the heating time scale is shorter than the characteristic time for hydrodynamic expansion, an explosive evaporation of the chromosphere results. Explosive evaporation takes place when the chromosphere is unable to radiate energy at a sufficient rate and consequently expands at high velocities into the overlying flare loops (Antiochos and Sturrock 1978; Zarro and Canfield 1989; Fisher et al. 1985a, 1985b, 1985c). The overpressure of evaporated material also drives a downward-moving radiative shock through the chromosphere. Kosovichev and Zharkova (1998) proposed that sunquakes are a manifestation of this shock penetrating through the photosphere and into the solar interior. However, passage of the transient through the lower chromosphere and photosphere is subject to heavy radiative losses that deplete the downgoing transient (see Hudson et al. 2008). Other possible contributors to flare acoustic emission include photospheric heating (Lindsey and Donea 2008), due to back-warming (Machado et al. 1989; Metcalf et al. 2003) or deeply penetrating protons, and magnetic jerks (Hudson et al. 2006). These will be discussed further in Sect. 9.

Recognizing that only a small fraction of the energy released in a large solar flare is deposited in the neighbourhood of the acoustic emission, Donea and Lindsey (2005) suggested that much weaker solar flares focused into compact foot points can induce significant seismic transients, hence sunquakes may not be rare events. They also argued in favour of the need for a source agent that acted relatively suddenly, a qualification further emphasized by Martínez-Oliveros et al. (2007, 2008a), who discovered significant seismic emission in relatively small flares.

A systematic survey, applying helioseismic holography to campaign observations from the MDI (Scherrer et al. 1995) aboard SOHO (Besliu-Ionescu et al. 2006; Donea et al. 2006a) discovered more than a dozen sunquakes during solar cycle 23. These developments have opened a cornucopia of new diagnostic resources in solar seismology and flare research. Fundamental to the development of these resources is an analytical understanding of the physics of flare acoustic emission and accessible observational manifestations of this phenomenon.

The role of high energy particles from flares associated with sunquakes was discussed for the non-thermal excitation, ionization and Ohmic heating of the ambient plasma by Zharkova and Zharkov (2007) as a cause of seismically quiet flares. Because of the particle collisions in flare plasmas, the strong soft electron beams deposit a large amount of energy in the corona and upper chromosphere producing strong soft and hard X-rays. Zharkova and Zharkov (2007) suggest that there is not much energy left for producing observable hydrodynamic shocks and sunquakes.

An important aspect of flare seismology is that of the magnetic field in the hosting active regions. This may be a crucial physical factor in the wave generation and absorption or conversion (Hudson 2000). Studies of the configuration and temporal behaviour of the magnetic field in active regions (Kosovichev and Zharkova 2001; Sudol and Harvey 2005; Kosovichev 2006b; Martínez-Oliveros et al. 2007, 2008a; Martínez Oliveros et al. 2008b; Martínez Oliveros and Donea 2009; Hudson et al. 2008) have attempted to explain the mystery of seismic events.

Crucial to the development of flare acoustic emission as a probe of flare MHD and subphotospheric thermal structure is a clear understanding of the physics of seismic emission from acoustically active flares and the various radiative signatures associated with them. Forward modelling of the physics of seismic emission from acoustically active flares is needed. This work will facilitate our understanding of the role of inclined magnetic fields, the role of fast and slow magneto-acoustic mode coupling in magnetic photospheres, subphotospheric thermal structure, and how wave generation by turbulence in active-region subphotospheres differs from that in the quiet subphotosphere. In this paper I will try to review the main properties of the seismic transients from flares as presently understood. I will use examples for each of the enumerated properties of the seismic sources generated by flares. For specific details, such as timing, exact positioning of a seismic source and databases of seismic transients I will refer to the corresponding references. I also refer the reader to a recent review by Kosovichev (2010). A very important question, to which the *Solar Dynamics Observatory* (*SDO*) promises a timely answer, is whether the ascending phase and the peak of solar cycle 24 will be more conducive to seismically active flares than was apparent in cycle 23.

2 Examples of Sunquakes

Kosovichev and Zharkova (1998) made the first identification of a seismic event in a form of acoustic wave ripples, emanating from the X2.6 flare of 1996 July 9. The Doppler signature in the source region had an amplitude of about 1 km/s. Donea et al. (1999) applied subjacent-vantage seismic holography (Lindsey and Braun 2000) to helioseismic observations of this flare to image the epicenter. The acoustic source of the X2.6 flare was centred on the composite umbra of the δ-configuration sunspot at the heart of the active region AR 7978. The dimensions of the seismic source were similar to the composite dimensions of the two oppositely polarised umbrae of the sunspot.

Seismic holography applied to the X17.2 flare of 2003 October 28 and the X10 flare of 2003 October 29—the "Halloween flares"—showed pronounced seismic emission from both of those flares (Donea and Lindsey 2005). Both of the Halloween flares were observed by a considerable array of other space-borne and ground-based facilities. The Halloween flares were somewhat less acoustically energetic than those of the X2.6 flare of 1996 July 9, but the seismic emission was more conspicuous, because of the relatively greater energy radiated at higher acoustic frequencies. The acoustic energy radiated into the 2.5–4.5 mHz p-mode spectrum generally exceeds that delivered in the 5.0–7.0 mHz band. However, because the ambient p-mode background that obscures flare-acoustic emission is so much quieter at the higher frequencies, the latter has invariably been far more conspicuous. The acoustic ripples emanating from the X17.2 Halloween flare were easily seen in the raw Doppler observations. Beginning with Donea et al. (1999) and Donea and Lindsey (2005), holographic identification of seismically active flares has capitalized heavily on the 5.0–7.0 mHz spectrum of the flare-acoustic transients, further recognizing superior spatial discrimination at the higher frequencies, owing to a *finer diffraction limit*. The Halloween flares, then, represent a major step in the development of flare seismology.

It is apparent that in most flares the energy stored in the corona is initially radiated from the chromosphere, as suggested by recent UV and white-light observations, and roughly confirmed for large flares in measurements of the total solar irradiance (Woods et al. 2004). Donea and Lindsey (2005) estimate the electromagnetic radiated by the X10 flare to be 4.5×10^{31} erg, with an acoustic energy of 1.3×10^{27} erg. Hence, the acoustic transient accounts for $\sim$0.004% of the electromagnetic, which is generally thought to be close to the total (Potts et al. 2010).

A very interesting aspect evident in the X17.2 flare of 2003 October 28 is the capacity of some flares to generate multiple seismic sources, identified by Donea and Lindsey (2005). The acoustic-transient signatures were co-aligned with the hard X-ray emission from the footpoints of coronal loops, suggesting a direct link between relativistic particles accelerated during the flare and the radiative response of the chromosphere during the chromospheric evaporation. GONG intensity observations showed a strong correlation between impulsive-phase white-light emission and the acoustic source distribution as determined by seismic holography.

Kosovichev (2006a, 2007) and Zharkova and Zharkov (2007) confirmed the major source locations identified by Donea and Lindsey (2005) based on the morphology and the location of the nearly circular expanding wave fronts emanating from the sources, which were clearly visible in the Doppler observations of the flare.

Besliu-Ionescu et al. (2005) and Moradi et al. (2007) reported one of the most powerful sunquakes detected to date, produced by the X1.2 solar flare of 2005 January 15 in active region 10720. This acoustic source distribution coincided the X-ray and impulsive-phase white-light emission. For further details, we refer to Donea et al. (2006a) and Kosovichev (2006a). The amplitude of the ring-like ripples radiating outward from the local impact site was up to about 100 m/s.

Suspecting that sunquakes could be much more common than previously thought, Besliu-Ionescu et al. (2005) quickly identified strong sunquakes in the X5.6 flare of 2001 April 6, the X2.3 flare of 2001 April 10, the X2.6 flare of 2001 September 24, the X3 flare of 2002 July 15, the X4.8 flare of 2002 July 23, and X1 flare of 2002 August 21. The flare of 2002 July 23 was conspicuous in lacking the signature of γ-rays, which would be needed to explain significant heating of the low photosphere other than by back-warming. Kosovichev (2007) studied the 2002 July 23, commenting on the lack of γ-rays and implications for photospheric heating. He also modelled anisotropies in the pattern of its acoustic emission as a signature of source motion. Kosovichev and Zharkova (2001) studied the acoustically inactive flare of 2004 July 14, which, while acoustically inactive, nevertheless showed Doppler and magnetic transient behaviour in magnetic foot points.

Further suspecting that relatively weak flares could produce sunquakes, Donea et al. (2006b) extended their survey to M-class flares, finding strong acoustic emission from the M9.5 flare of 2001 September 9 at 20:40 UT. They have extensively analysed the seismic transient of this flare. Besliu-Ionescu et al. (2006) found a few more M-class acoustically active flares. The M9.4 flare of 2004 August 15 showed both a strong mass flow in the host active region and also flare-driven seismic waves. Martínez Oliveros et al. (2008b) also reported a seismic transient in the M7.4 solar flare of 2004 August 14 (AR 10656).

3 Sunquakes from X-Class Solar Flares

During solar cycle 23 (SC23), lasting from 1997 to 2007, the Sun generated 124 X-class solar flares according to the solar database of the National Geophysical Data Center (ftp.ngdc.noaa.gov). SC23 was a low-activity cycle compared to the previous solar cycle. Our systematic survey for seismic flares revealed that of 124 flares, 34, 30% of the total, were generated close to or at the solar limb, where helioseismic holography cannot be applied.

A significant number of flares, 44 (some where extremely energetic) did not have a good SOHO/MDI data coverage. This reduces the number of SOHO/MDI measured solar flares by another 35%. Continuous SOHO/MDI Dopplergrams data sets were available for only a third of the total number of X-type flares for the SC23. Figure 1 shows the distribution in the number of sunspots (bright-orange region) in SC23. The total number of X-class solar flares (underlying pink region). Dark filled circles show the mark X-class acoustically active flares. Despite the fact that this graph suggests that there were more solar quakes generated during the declining phase of the solar cycle, we should treat this result with caution.

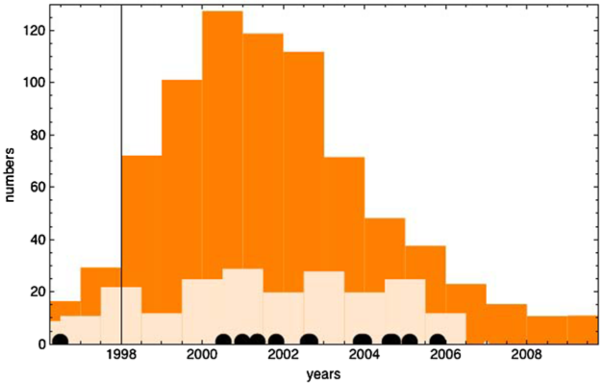

Fig. 1 Solar Cycle 23: The annual variation of number of solar spots (*filled area*); The number of X-class solar flares (*yellow dots*) produced each year. *Dark filled circles* show the position in time of the detected seismic sources generated by X-type solar flares

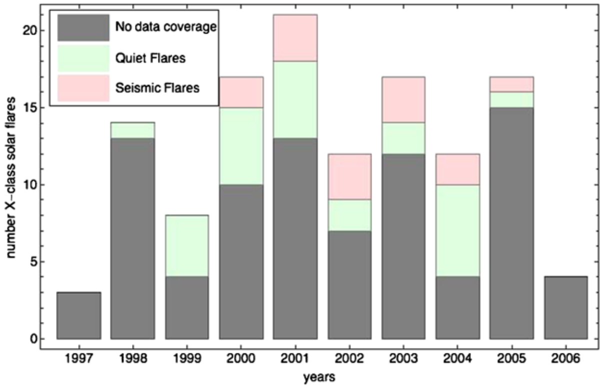

Fig. 2 Bar Chart of the X-class solar flares of cycle 23. *Grey area* represents the number of solar flares in a year either located at the solar limb or with poor MDI-data coverage; *Light green areas* show the number of aseismic flares which also had a good MDI-data coverage; *Light red areas* show the number of seismically active flares detected per year. Some of these produce ring like waves known as sunquakes on the solar surface

Figure 2 shows a bar chart classifying X-class solar flares from 1997 to 2006. Following our survey of solar quakes, 12 X-class acoustically active flares were found in *SOHO*/MDI observations. We remark that SOHO/MDI data coverage for the majority of the X-type solar flares produced from May 1996 to February 2000, during the ascending phase of SC23 was very poor. Therefore, it is early to say that solar flares during the ascending phase of SC23 are a "superficial" coronal phenomenon not affecting much the solar surface and interior. However, if this would be the case, then indeed the effect of the solar cycle on sunquakes is worth exploring. Knowing that the SOHO/MDI covered only a fraction of the flares for SC23, it would appear that the Helioseismic Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO), if operated over the full term of solar activity cycle 24, will observe scores of new sunquakes, conservatively and elucidate the possible connection between the solar cycle and the seismicity of flares. Only then will we be able to check whether sunquakes display solar-cycle effects.

Interestingly, accordingly to Joshi et al. (2006) solar activity dominated in the northern hemisphere during the rising phase of SC23 (1997–2000). The dominance then moved to the southern hemisphere after the solar maximum in 2000. Li et al. (2009) predicted that for the forthcoming cycle 24, an asymmetry of solar activity will occur with solar activity remaining dominant in the southern hemisphere. For SC23, we did not detect any preference of solar flares to generate sunquakes in one hemisphere or another. However, this is an interesting aspect of solar activity, and with better statistics for the seismic transients of the cycle 24, including the high, full-disk coverage we are getting from *SDO*/HMI, we should be able to check whether the shift in dominance of one hemisphere over the other one has any significance to the production of sunquakes.

4 Reading Helioseismic Maps of Solar Flares

Helioseismic analysis of sunquakes has relied on full-disk Doppler maps at a cadence of about 60 s and a resolution of ∼3 Mm. These have been provided by the space-borne *SOHO*/MDI and the ground-based Global Oscillations Network Group (GONG) during SC23 in the photospheric line Ni I 6768 Å. The same are now being provided by *SDO*/HMI in the photospheric line Fe I 6173 Å, at a cadence of 45 s and resolution of ∼1.0 Mm.

Let us sumarize the case of the well studied X1.2 solar flare of AR10720 on 2005 January 15 (see Fig. 3 and Moradi et al. 2007; Martínez-Oliveros et al. 2007; Kosovichev 2006a). The SOHO/MDI Doppler maps show the velocity impulse (amplitude 100 m/s) of the flare in the sunspot photosphere which was almost as sharp as the HXR flux detected in the 4–25 keV energy range by the RHESSI satellite. The upper left map in Fig. 3 shows the Doppler difference between two consecutive solar images at 0:41:30 UT on January 15, 2005; the bright elongated feature indicated by the arrow in the upper left frame signifies a strong red shift, suggesting a downflowing photospheric plasma. Another interesting example is the X17 flare of 2003 October 28, which showed multiple seismic sources. Transient red shifts at the locations of the strongest three cases showed downward velocities of 2.15 km/s, 2.0 km/s and 1.75 km/s (Donea and Lindsey 2005; Zharkova and Zharkov 2007). The durations of the downward motions did not exceed 2.0 minutes followed by a relaxation of the photosphere back to the preflare status. Simple calculations show that the momentum required to produce the observed seismic response is about 10^{21-22} g/cm/s for an average shaken area located under the flare of 3–5 Mm across (Kosovichev and Zharkova 1998).

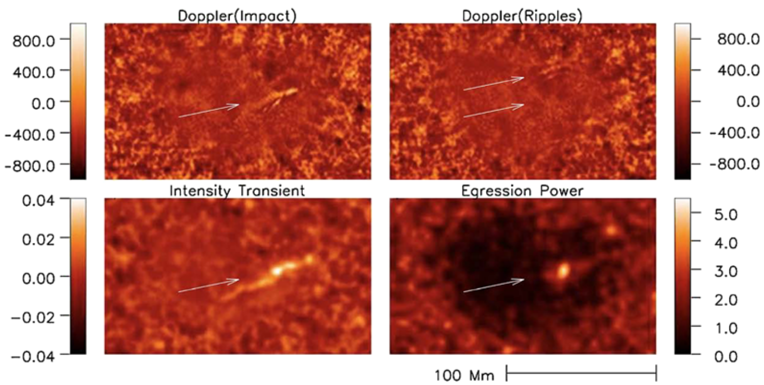

Fig. 3 X1 flare of 2005 January 15. *Upper left panel* shows an MDI Doppler image at flare onset with *arrow*, reproduced in all other frames, pointing to the sudden, compact *red-shift* signature at the acoustic source. *Upper right panel* shows the MDI Doppler map 40 minutes after the onset of the flare. The *top arrow* in this frame points to surface Doppler ripples proceeding outward from the impact site, located by the *lower arrow*. *Lower left panel* shows the signature of sudden visible continuum emission observed by GONG. *Lower right panel* shows the signature of the extended seismic source acting in the 5–7 mHz spectrum, reconstructed at the time of flare onset from the surface ripples that subsequently spread outward through a 15–45 Mm pupil centered on the pixel for each pixel in the image

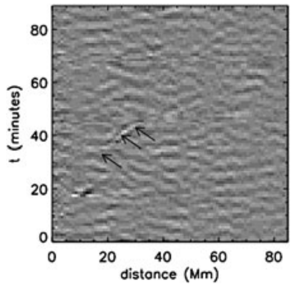

Fig. 4 Time-distance diagram of the seismic response of the photosphere during the X1 flare of January 15, 2005. *Arrows* point to the visible part of the ridge which represents the expanding Doppler ripples from the seismic source

Once the location of the hydrodynamic flare impulse is identified among the 5 min photospheric oscillations, we can then use two different, but in our opinion, complementary helioseismic techniques to detect acoustic sources generated by a solar flare.

The first method involves analysing time-distance plots (Kosovichev and Zharkova 1998; Martínez Oliveros et al. 2008b; Kosovichev 2006a; Zharkova and Zharkov 2007). We can generate time-distance plots over a selected range of azimuths to gauge the expanding-wave signal from the supposed source point and compare this signal with a curve that represents the theoretical group velocity. The resulting signature, if visible enough, is manifested as a "ridge" in the time-distance diagram (Fig. 4). The slope of this ridge decreases with distance from the source, meaning that the seismic waves accelerate. Examining time-distance diagrams from different prospective source points helps to identify the actual origin of the seismic waves. Pre-filtering the observations for relatively high frequencies, i.e., 5–7 mHz, improves the visibility of the ridge signature.

A second method is helioseismic holography applied to the Doppler observations to reconstruct the acoustic emission of X-flares. In this application, seismic holography renders phase-coherent "acoustic egression power" movies of the sources that gave rise to the surface disturbances. The seismic sources appear as bright pixels in egression power snapshots representing the impulsive phase of the flare (see the lower right panel of Fig. 3). Each pixel in this map is a coherent representation of acoustic waves that have travelled thousands of km from that pixel, the focus computation, deep beneath the solar surface, to re-emerge into an annular pupil 15–45 Mm from the focus. Basic principles of seismic holography are reviewed by Lindsey and Braun (2000) (see also Gizon and Birch 2005). Applications of subjacent seismic holography to flare seismology are described by Donea et al. (1999) and Donea and Lindsey (2005).

The X1 flare of 2005 January 15 is an instance of a relatively small flare in which nearly all of the energy released, i.e., the white-light emission, emanated suddenly from a single, highly compact source region. Of all the SC23 sunquakes, this was probably the most spectacular in terms of its raw post-flare Doppler signature (upper right panel of Fig. 3), with an egression-power signature of 3.4×10^{27} erg. Seismic emission from the X17.2 flare of 2003 October 28 was ∼32% greater, but this flare was many times more energetic, and its egression-power signature, of 5.6×10^{27} erg, was the cumulative emission from multiple source regions over many times the area of the acoustic source of the X1 flare. Indeed, most of the white-light emitted from the X17.2 flare emanated from outwardly expanding, relatively diffuse ribbons up to 15 minutes after the impulsive phase. This exemplifies our understanding that what drives seismic emission from flares is an agent that acts relatively suddenly in a relatively compact region than necessarily a highly energetic one.

The "hardest" seismic emission was that of the X1 2005-January-15 flare. The 10^{27} erg emitted in the 5–7 mHz band is the greatest of all of the SC23 flares captured by MDI, which accounts for its exceptionally conspicuous signature in raw Doppler observations. The X2 flare of 1996 July 16 was acoustically the most energetic of the SC23 flares, emitting 7.7×10^{27} erg, but this was unusually "soft" emission, disproportionately distributed into the 2.5–4.5 mHz band, with only 2.4×10^{26} erg in the 5–7 mHz band. It was, accordingly, much less conspicuous in raw MDI Dopplergrams. We do not have white-light observations of this flare.

5 Location and Morphology of Seismic Sources

Seismic emission from flares has emanated from within or near sunspot penumbrae in almost all instances encountered to date. This is particularly interesting, because the magnetic field is generally highly inclined from vertical in penumbra.

The 2005 January 15 flare emanated from a δ-configuration sunspot. It reveals that the velocity impulse of the flare in the sunspot photosphere was almost as sharp as the HXR flux detected in the 4–25 keV (0.5–4 Å) energy range by the *GOES* satellite. The region where the maximum velocity depression occurred at the photosphere shows the first significant Doppler impact that the flare could have in the photosphere, at 00:41:00 UT. This appears as a sudden red shift of up to $\sim$400 ms^{-1} in the mean velocity of the Doppler signal distributed along the magnetic neutral line separating the major umbral components of the sunspot, suggesting a downward motion of the photosphere, observed in the 3-minute period during the start of the flare.

A close facsimile of the transient white-light signature is seen in the 6 mHz egression-power map, in the lower right panel of Fig. 3. About half of the excess acoustic emission is from a central kernel approximately 15 Mm in diameter. Further excess emission is distributed along the magnetic neutral line, approximately cospatial with the transient excess in white-light emission and the transient Doppler signature. Donea and Lindsey (2005), Moradi et al. (2006b) and Martínez-Oliveros et al. (2008a) have drawn attention to the close correlation between the transient component of white-light emission, with Lindsey and Donea (2008) specifically comparing egression-power and intensity-power variations in the 5–7-mHz band and seeing a remarkably close match.

Except during large flares, egression-power maps invariably show considerably less acoustic power emanating from magnetic regions than from the quiet Sun. This considerably strengthens the statistical significance of the acoustic emission from the flare.

In fine detail, the acoustic sources frequently show the morphology of 2–3 narrow kernels stacked together, separated by intervening nodes. Donea et al. (1999) suggested that this was the result of interference caused by rapid motion of the source in the direction along which the kernels were stacked. This proposition was strongly supported by Donea and Lindsey (2005) who found a similar stacked-kernel structure in the acoustic sources of the flares of 2003 October 28 and 29, for which the motion of the hard X-ray RHESSI (HXR) sources were indeed aligned accordingly with the stacks.

Besliu-Ionescu et al. (2007) analysed the Hα emission of the 2003 October 29 and 2004 July 16 solar flares. They found that Hα emission is mostly related to the post-impulsive phase of the flare, emanating from ribbons outside of the impulsive foot points and the acoustic source. However, Donea and Lindsey (2005) found strong red-shifted emission from NaD_1 at the two impulsive-phase footpoints of the flare of 2003 October 29, one of which coincided with the single significant acoustic source of that flare.

The seismic sources can also have the morphology of a compact kernel $\sim$10 Mm in diameter situated on the magnetic neutral lines. In some cases (e.g., the 15 July 2005 seismic transient) the source presents an additional seismic diffuse distribution spread along the neutral line of 45 Mm in Moradi et al. (2007). The seismic source of the 13 August 2004 flare triggered in AR10656 at 18:10 UT. The kernel-like structure of this signature suggested that the seismic source was in motion, parallel to the magnetic neutral line, with a north-west direction of motion.

6 Magnetic Configuration of Coronal Loops

The link between the magnetic configuration (topology) that leads to the energy release at low altitudes in sunquake events was first suggested by Kosovichev (2006b). The evidence provided by Martínez-Oliveros et al. (2007, 2008b) suggests that low lying coronal loops are more likely to be conducive to a more rapid injection of trapped electrons into the chromosphere at their footpoints. This enhances the magnitude and suddenness of the chromospheric heating that gives rise to the intense visible continuum emission seen in all flares with detectable seismic activity. Consequently, this could facilitate seismic emission into the solar interior. Recently, the work by Hudson et al. (2008) considered the back reaction on the photosphere and solar interior by the magnetic field evolution required to release flare energy. The photospheric magnetic fields appear to become more horizontal after a flare (Wang and Liu 2010). If this occurs sufficiently suddenly, then it can apparently excite a sunquake.

7 Flare Signatures in Visible Continuum Emission

Flares with substantial emission in the visible continuum are called white-light flares. Certain aspects of white-light continuum emission are still a puzzle, such as the source height. Energetic particles play a crucial role in the energy transport of flares (Neidig and Kane 1993). Interestingly, in most flares the energy stored in the corona is radiated in the chromosphere, as established by recent UV and white-light observations, and confirmed for the first time in the total solar irradiance (Woods et al. 2004).

Even more, the spatial and temporal correspondence between impulsive continuum emission and the seismic signatures from some flares suggests a strong connection between seismicity and sudden white-light emission.

Using GONG intensity observations Donea et al. (2006b) estimate the total electromagnetic energy radiated from the location of the seismic source to be $\sim 1.2 \times 10^{30}$ erg. Based on the egression-power signature they also estimated the seismic energy radiated into the 15–60 Mm pupil in the 2.0–7.0-mHz spectrum to be 1.6×10^{27} erg, with the 5.0–7.0 mHz emission 12.5% of the total. The seismic energy radiated by the M9.5 flare therefore appears in this case to be ∼0.13% of the electromagnetic energy radiated by the flare, much greater than for the large Halloween flares, but still a small fraction of the total.

'White-light' radiation (previously thought to occur only in the most energetic flares) has also been found in small (C-class) flares Hudson et al. (2006) and even one yet smaller flare of class B (Jess et al. 2008). Similarly, in flare seismology it has been shown that even small M-class flares (with white-light emission; see Sect. 3, last paragraph) can generate significant seismic events.

The best examples suggesting that heating of the low photosphere associated with impulsive white-light emission could contribute significantly to seismic transient emission are the following:

– The X1 flare of 2005 January 15 is one of the clear examples, where the white-light emission from the flare has the same morphology as the seismic source at 6 mHz. Figure 3 (lower left frame), shows the excess continuum intensity observed by the Global Oscillations Network Group (GONG) in the impulsive phase of this flare, and other helioseismic signatures.
– The impulsive phases of the flares of 2003 October 28 and 29: the maximum intensity enhancement in the X10 flare October-29 flare was 37%. An even more conclusive result came with the close match between the maps of the 5–7 mHz acoustic energy flux (egression power) and acoustic emission based on the 5–7 mHz spectral power of the intensity continuum transient. It must be understood that in these large flares the acoustic emission emanated only from the regions of very sudden white-light emission. Most of the continuum excess was temporally diffuse, and no detectable acoustic emission came from this component.
– M-class solar flare of M9.5 displayed a seismic source with a kernel-like structure which is also identified in the white-light flare emission. In this instance, nearly all of the continuum excess was sudden, and focused into a very compact region.

In summary, then, the more compact the concentration of white-light emission, both spatially and temporally the greater the efficiency of seismic power emission into the solar interior underlying the region from which the excess continuum is radiated. Interestingly, in some acoustically active flares, the seismic kernels, as well as the white-light kernels, have two distinct features, a bright inner core and a fainter halo (asymmetric). Acoustic-emission kernels have generally been located mostly within the penumbrae of sunspots. No kernel in the quiet areas of the Sun was detected.

Considering a simple, non-magnetic model of the photosphere, Donea et al. (2006b) estimate that the acoustic spectrum seismic emission driven by photospheric heating should be closely proportional to the power spectrum of the white-light flux, substantially above the photospheric acoustic cut-off frequency. Hence, if photospheric heating is the sole contributor to flare acoustic transients, the 5–7 mHz intensity continuum power maps should look very similar to the seismic maps in the same band. This appears to be the case in the X10 flare of 2003 October 29 (Lindsey and Donea 2008).

8 Excitation of Seismic Transients in the Solar Photosphere

If we can sufficiently understand how the flare distributes its energy into radiation, flows, heat and particles, then we may be able to solve the puzzle: Why some large flares did not generate sunquakes. Various scenarios have been proposed to explain the solar seismicity generated by flares:

1. Kosovichev and Zharkova (1998) propose that sunquakes are generated by chromospheric shocks resulting from the explosive ablation of the chromosphere by high-energy electrons. These shock are heavily damped by radiative losses in the chromosphere and upper photosphere. Hudson et al. (2008) express doubt whether such a shock can survive passage through the photosphere to reach the solar interior with energies estimated for sunquakes.
2. Donea et al. (2006b) suggest that impulsive heating of the low photosphere, observed as an excess in the visible continuum emission (radiative back-warming) can contribute significantly to flare acoustic emission. The main point to bear in mind is the need for an account for back-warming in hydromechanical simulations of thick-target heating of the chromosphere.

3. The direct interaction of high-energy protons with the photosphere, observed in some seismically active flares, has also been considered as a possible mechanism (Donea and Lindsey 2005; Zharkova and Zharkov 2007) for heating of the photosphere leading to seismic excitation, but some acoustically active flares have lacked the signature of protons sufficiently energetic to heat the photosphere sufficiently to drive significant seismic emission.
4. Finally, Hudson et al. (2008) suggested as a result of the reorganization of the coronal magnetic field, that magnetic field lines relax to a configuration of lower-lying flux tubes. This both reduces the total amount of energy in the magnetic field and increases the field inclination from vertical at the foot points. The reduction in magnetic energy drives the flare. The shift in inclination at the foot points induces a Lorentz-force transient, i.e., a "McClymmont Jerk," that could contribute to seismic emission into the underlying solar interior if sufficiently sudden.

Regardless of the method of transportation of some of the flare energy into the photosphere, the first step that needs to be understood is how accelerated particles, after injection into the chromosphere, transport and deposit energy in the lower atmosphere, resulting in hydrodynamic responses (chromospheric shock). The description of how particle precipitation leads to shocks and ionization/heating of the lower atmosphere is by itself a very broad topic, which we will not tackle in this review. Instead we will mention that the ambient plasma response to the injection of accelerated particles is described by the hydrodynamic equations (Kostiuk and Pikelner 1975; Somov et al. 1981; Fisher et al. 1985a, 1985b, 1985c, and references therein).

The chromospheric condensation wave driven by the pressure increase from the heated upper and middle chromosphere escapes the region with velocities of 20–40 km/s (Fisher et al. 1985a, 1985b, 1985c) carrying a fraction of the thermal energy invested into thick-target heating of the chromosphere. However, the radiative losses rapidly deplete the shock of its energy. With significant uncertainties due to incomplete temporal coverage, this appears possibly to be the case of the eastern footpoint of a magnetic loop in the 2003 October 29 flare where the NaD_1 line profile did not show strong redshifted (downward) chromospheric motion but relatively little white-light and acoustic emission.

According to Fisher et al. (1985a) for intense flare heating parameters, the disturbance pressure can reach a maximum of 100–1000 dyne/cm^2. This is equivalent to a chromospheric wave reaching a column depth of $N \sim 10^{22}$ cm^{-2}, which is 2 orders of magnitude smaller than the column depth of the photosphere. Modelling of this process invariably shows only a small fraction of the energy initially invested in the shock penetrating into the photosphere (Allred et al. 2005). Based on this, Hudson et al. (2008) estimate that the energy penetrating into the deep photosphere is insufficient to explain the helioseismic signatures, especially in low class solar flares.

Fisher et al. (2011, Canfield fest conference) compared shock penetration to the integrated vertical Lorentz force on a volume heated by the flare at the photosphere and found a magnetic pressure pulse of $\sim 2.5 \times 10^3$ dyne/cm^2. The magnetic field undergoes a rapid change during the flare impulsive phase, it becomes more horizontal, shifting the direction of the photospheric Lorentz force. If the shift is sufficiently sudden, it can drive an acoustic transient from the photosphere into the solar interior.

Direct heating of the low photosphere by high-energy electrons would be hard to explain in the context of a "canonical" flare model (Hudson et al. 1992; Neidig 1989). According to Machado et al. (1989) only highly energetic electrons with energies above a few MeV, can reach the photosphere. The question emerges, then, how moderate-sized flares can generate seismic transients at the photospheric level. The new observations from Solar Optical

Telescope on Hinode have a spatial resolution of 0.2–0.3 arcseconds, sufficient to examine in details the flare chromospheric properties. A few flares show significant UV and white-light emission from chromospheric footpoints with a very small area (10^{16} cm^2, Isobe et al. 2007). Small-footpoint areas challenge models of flare energy transport by an electron beam from the corona. Accordingly to Fletcher et al. (2007), electron flux for these flares approaches or exceeds that which can be realistically supplied by the coronal medium. This calls for reconsidering the role of coronal electrons in flare energy transport.

If we take into account the "canonical model" of flares, radiation can be produced in the chromosphere as a result of high-energy electrons ionizing chromospheric hydrogen down to about the temperature minimum (Hudson 1972; Zharkova and Kobylinskii 1993). This emission is mainly in the Balmer and Paschen continuum, occurring after the recombination on time scales in the range 10–100 s (Zharkova and Kobylinskii 1993; Machado et al. 1989). The suggestion is that flare-generated acoustic transients can be driven by transient photospheric heating that is closely associated with the continuum emission observed. The excess continuum emission could be the direct signature of a heated photosphere. However, a direct result of such a radiative flux emanating from some layer above the photosphere would likewise be a heated photosphere. The photosphere absorbs part of this radiation that is emitted downward and is heated up to ∼400 K in excess of its pre-flare temperature (Allred et al. 2005). The almost instantaneous effect of this absorption in the visible spectrum is mostly dissociation of the negative hydrogen H^- ions, which represent the predominant source of photospheric opacity (Vernazza et al. 1981). The result is a nearly immediate relaxation to thermal equilibrium between local ionization and kinetic temperatures, bringing about a commensurate rise in the latter at the expense of the former and a proportionate increase in pressure, which drives an acoustic transient into the subphotosphere.

Timing is also a very important issue when it comes to understanding the generation of sunquakes. Based on the acoustics in a non-magnetic chromosphere, in order to drive a wave that substantially penetrates beneath the chromosphere and photosphere into the solar interior, the agent that drives the wave must act relatively suddenly. The acoustic cut-off time-scale of the low photosphere is ∼45 s. A gradual force applied to the base of the photosphere, with characteristic time exceeding ∼100–200 s cannot drive a strong acoustic transient in a low-photosphere. This could explain the relative "hardness" of sunquake acoustic spectra cited in the itemized list in the Introduction. The element of impulsiveness is critical to consideration of the contribution of back-warming to flare acoustic emission, proposed by Donea and Lindsey (2005) and Moradi et al. (2007), see also Lindsey and Donea (2008).

9 Ripples from Seismic Sources

Seismic waves generated by flares manifest themselves at the solar surface, as a quasi-circular pattern of ripples moving away from the flare epicentres. Kosovichev and Zharkova (1998) have identified ripples from the 1996 July 9 flare. The horizontal speed of propagation of the waves accelerated from approximately 30 km/s at a distance of 20 Mm from the epicenter of the sunquake to 100 km/s (at a distance of 120 Mm). The amplitude of the Doppler velocity is 50 km/s. Donea et al. (1999) estimated a total acoustic energy of roughly 10^{28} ergs for this seismic source. The observed waves are unlike water ripples, in that they accelerate with increasing distance from their source. This is explained by the fact that waves travel downward into the hotter and deeper layers of the Sun, where the sound speed increases, before being refracted back to the surface. Components of the disturbance that return to the surface further from the source followed a path that penetrated deeper beneath the photosphere, where the sound speed is higher, hence the higher apparent speed of the surface disturbance at greater horizontal distances. The acoustic waves travel back up to the solar surface and shake the photosphere, producing seismic ripples.

Ripples on the solar surface from seismic sources were simulated in 1995 by Kosovichev and Zharkova (1995). Medrek et al. (2000) and Podesta (2005) also investigated the propagation of sunquake waves using a numerical solution of the compressible and incompressible Euler equations. An interesting characteristic feature of the seismic response of most sunquakes is a considerable anisotropy in acoustic amplitude of the ripples from the vantage of the source (Kosovichev 2006a; Moradi et al. 2007). I.e., the acoustic emission is much stronger in some directions than others. The manifestation of this in egression-power maps is the "stacked kernel" character mentioned in Sect. 5. This observation was interpreted by Donea et al. (1999) as due to a source having a temporal dependence along the main axis of the anisotropy, and confirmed by Donea and Lindsey (2005), who noted the motion of the HXR and white-light sources, supposing that these acted as the acoustic source. Indeed, the main axis of the anisotropy proved to be well aligned with the direction of motion of the hard X-ray RHESSI flare kernels of the Holloween 2003 flares, for example Donea and Lindsey (2005). Kosovichev (2007) modelled the source of the 2002-July-23 sunquake as the signature of a moving beam of accelerated particles bombarding the photosphere. With a source speed of 25 km/s, the resulting anisotropy was a realistic match to that of the helioseismic observations, with an enhanced amplitude in the direction of motion from the source.

A useful control diagnostic of source anisotropy can be devised from seismic holography by isolating the component of surface-wave motion in Doppler observations of a sunquake that has emanated from the supposed source region of the sunquake, assuming that the subsurface acoustic evolution obeys standard non-magnetic wave mechanics in a standard model, such as Christensen-Dalsgaard (1997). This exercise is applied here to the seismic source of 15 January 2005 flare, for which an instance of its acoustic transient at the photosphere is presented in the egression power map, shown in Fig. 3, lower right panel. We first compute the coherent seismic egression, $H_+(\mathbf{r},\omega)$, of the Doppler-acoustic field, $\psi(\mathbf{r},\omega)$, as prescribed by Donea et al. (1999), the power, $|H_+(\mathbf{r},\omega)|^2$, of which is rendered in the lower-right panel of Fig. 3. We then apply a spatial mask to $H_+(\mathbf{r},\omega)$, admitting just the source region as determined by the egression-power signature (see the signature in centre of the lower-left frame in Fig. 5). Finally, we reverse the egression computation, by applying the *in*gression extrapolation to the masked egression.[2] The result is a representation of the acoustic field emanating from the masked region with the p-mode noise from the many other sources in the solar environment greatly suppressed.

Comparative results are shown in Fig. 5. The seismic ripples (the sunquake) are seen propagating preferentially in the northward direction from the source. The enhanced northward amplitude is consistent with a northward motion of HXR footpoint motions across the source region during the impulsive phase of the flare, as described by Moradi et al. (2007). Kosovichev (2007) discussed the anisotropy mentioning that the strongest amplitude is observed in the same direction as the direction of motion of flare ribbons. Figure 5 renders the anisotropy of the excess acoustic emission from the most conspicuous component of excess

[2]In this application, the computation of the acoustic egression is a single-skip extrapolation of the acoustic field, ψ, backwards in time. The *in*gression is a single-skip extrapolation of its argument forward in time. Without masking, the application of the ingression extrapolation to an egression extrapolation of ψ returns ψ itself, provided that both extrapolations are made over an appropriately extended pupil.

acoustic emission, rather than to attempt a quantitative match of amplitudes of the excess acoustic emission with the same in the Doppler observations.

In summary, then,

(a) The maximum amplitude of ripples emanating from a moving source is generally along the axis of motion of the source, displaced from the source location in the direction of motion. This is consistent with the motion of the HXR footpoints which progress significantly across the acoustic source.
(b) Near a moving source, ripples near the source tend to have an elliptical shape, because of the spatial extension of the source domain in the direction of motion over the time frame of the acoustic emission.

In closing this section, we mention, as a note of caution, that seismic waves can be significantly depleted of their energy when crossing magnetic regions, and the helioseismic signature of seismic waves in a magnetic region are considerably suppressed. It should therefore be borne in mind that magnetic regions in the pupils of egression-power computations can lead to significant systematic underestimates of acoustic energies released by sunquakes, and introduce spurious asymmetries in their azimuthal distributions.

10 Radiative Hydrodynamic Simulations of Solar Flares

The relationship between flares and the seismic waves can supply us with information about the environment within which the latter propagate. The ripples as analysed in Sect. 9, provide us with only limited details about the entire event. The radiative environments of flaring chromospheres and photospheres are still poorly understood, and this is essential for the evolution of sunquakes. Numerical simulations offer an especially promising tool for an improved understanding of these environments. An especially powerful tool for studying the flaring atmosphere is the code RADYN (Carlsson and Stein 1992, 1995, 1997; Allred et al. 2005) which performs radiative hydrodynamics modelling of flares for a range of heights in the atmosphere, all the way down to the photosphere. Besliu-Ionescu (2010) analysed the generation of transients at the photospheric level, using RADYN, with a pre-flare atmospheric model of a quiet Sun, similar to Abbett and Hawley (1999) and Allred et al. (2005). The most exciting result of this work is that coincidentally with the onset of the thick-target heating of the chromosphere a sharp transient is produced in the low photosphere. Such a transient was predicted by Donea et al. (2006b) and is a result of immediate back-warming by the intense continuum emission. However, the conditions simulated were equivalent to a very weak flare, and the transient thereby delivered was far below the detection threshold for helioseismic observations.

Recently, Cheng et al. (2010) used the RADYN code to study the role of non-thermal electron beams in increasing the continuum emission in the lower photosphere. Their initial atmospheric model was based on a more realistic sunspot model. The most interesting aspect of this recent work, relevant for the seismology of flares, is that the energetics of the outer atmosphere in the simulations show how back-warming can efficiently heat the lower atmosphere to produce the observed continuum emission. In their Fig. 6, the heating rate (per unit volume) by the electron beam and by radiation are compared at various heights. For a large particle flux, one can see that at the photospheric level, the radiative heating dominates over the electron heating. In conclusion, the simulations by Cheng et al. (2010) reinforce the hypothesis that back-warming plays a major role in bringing enough flare energy into the lowest layers of the atmosphere to excite a detectable seismic transient.

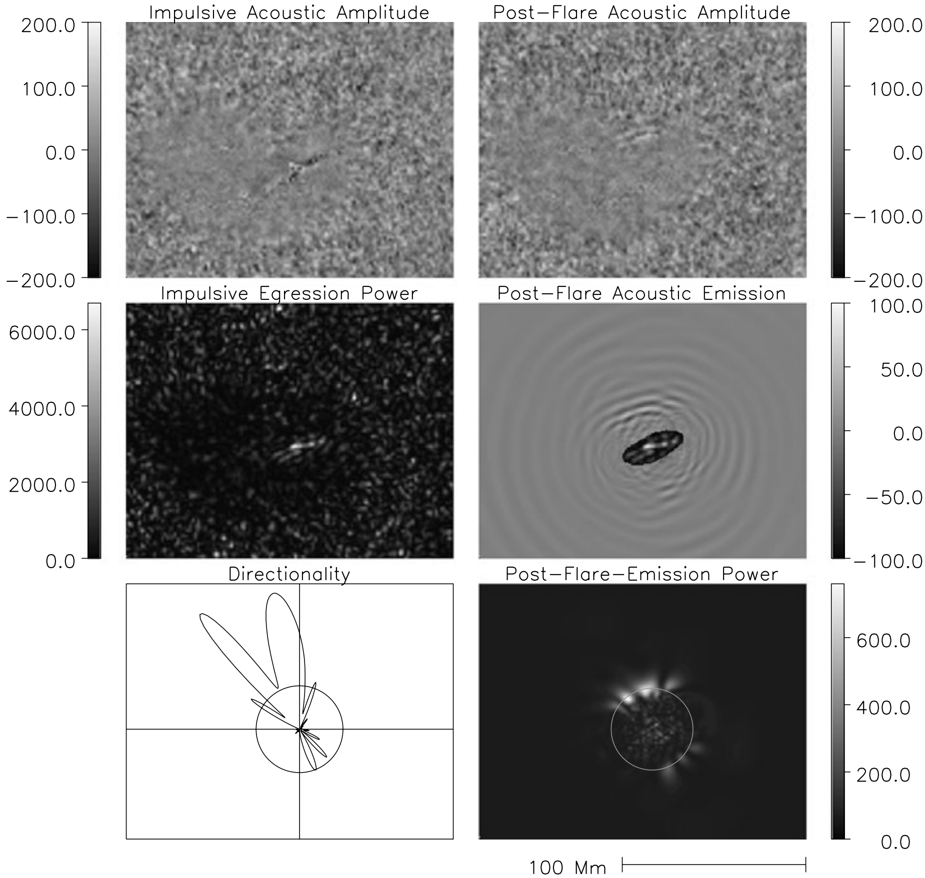

Fig. 5 An-isotropic quality of 5–7 mHz seismic emission from the flare of 2005 January 15. *Top left frame* shows the 5–7 mHz disturbance during the impulsive phase of the flare in m/s. *Top right frame* shows the same 18 minutes thence. *Bottom-right frame* renders the egression power extrapolated to the impulsive phase, in m^2/s^2. *Bottom right* shows the component of the acoustic disturbance emanating from the source region. The source region is represented by the paramecoid inset of the egression-power in the source region in the centre of the *lower-left frame*. *Lower-right panel* shows the acoustic power, emanating from the source region 24 min after flare onset. *Lower-left panel* plots the acoustic power, along the 22.4 Mm radius circle in the lower-right frame. The *circle* plotted in the *lower-left frame* represents an egression power of 200 m^2/s^2

The basic principle is that the radiation (that so heavily depletes chromospheric shocks) heats the photosphere, the result of optically-thick H^- bound-free absorption (Mihalas 1978), which then introduces a pressure transient directly to the underlying medium. Once the transient has penetrated substantially beneath the photosphere, significant radiative losses are blocked by highly opaque ionized hydrogen, whence the transient proceeds undamped from thence until its next encounter with the solar surface. Recent work by Fletcher et al. (2007), Potts et al. (2010) estimated the optical depth of the white-light-emitting layers region and stress the importance of the pre-flare chromosphere.

This leads us to another point of our analysis, related to why some small M class flares, are able to generate sunquakes whereas some powerful flares, such as the X5.3 Bastille day flare of 2000 remained seismically quiet. It must be born in mind, however, that the energy carried into the solar interior by the acoustic transient is never more than a fraction of a percent of that seen in visible continuum emission (see Sect. 8). Until possible contributors are better understood, then, even C class flares cannot be excluded from the list of possible seismically active events.

All seismically active flares observed to date have been impulsive white-light flares. Jess et al. (2008) showed that small flares can also be white-light flares, but with a continuum contrast very small. If back-warming is the mechanism, we expect seismic emission only in proportion to the square of the white-light luminosity—for a given spatial distribution. On the other hand, if the white-light is sufficiently concentrated, then even a small white-light flare can excite significant seismic emission.

Clearly, more simulations of acoustic emission due to back-warming in flares are needed. A very important step is required: to use the RADYN code to run back-warming simulations focused on a region resembling a more realistic umbral–penumbral photosphere. And, a major issue yet to be addressed in flare mechanics is the role of coupling between fast-, slow- and Alfvén modes in the transport of acoustic energy through the photosphere and into the solar interior (Cally et al. 2003; Cally 2000).

Increasing interest is now being paid to the hypothesis that Lorentz-force transients resulting from magnetic reconnection in coronal loops are a significant contributor to flare acoustic emission. Substantial shifts in magnetic signatures have been detected in a number of flares, some of which were acoustically active and others of which were not. Zharkova and Kosovichev (2001) examined the role of magnetic variations in wave generation, both coronal and chromospheric, based on magnetic signatures in the flare of 2000 July 14. This flare was acoustically inactive as far as helioseismic analysis to date has been able to discriminate. Sudol and Harvey (2005) measured localized variations in the line-of-sight magnetic field in a variety of flares, including the acoustically active flare of 2003 October 29. Donea et al. (2006b) found a strong local variation in the line-of-sight magnetic variation of the M9.5 flare of 2001 September 9 coincident with the source region of strong transient acoustic emission. The transient nature of all of these signatures is subject to significant uncertainty as what effects transient variations in the thermal and radiative environment of the flaring photosphere and chromosphere have on magnetic signatures if, for instance, the true magnetic field is constant. Hudson et al. (2008) advance the hypothesis that transient shifts in magnetic signatures during the impulsive phases of acoustically active flares are the result of flare-related magnetic reconnection and a source of flare acoustic emission. They estimated the mechanical work that would be done on the photosphere by a sudden shift in magnetic inclination consistent with observed magnetic signatures, hence invested into wave motion. They found energies roughly consistent with energy estimates based on helioseismic measurements of sunquakes and concluded that Lorentz forces may produce seismic transients comparable to those inferred from the helioseismic observations. Further study of this mechanism is needed.

11 Summary

The aim of this review paper was to give an updated summary of our present understanding of seismic transients from flares. Observations have firmly established that some flares release strong seismic transients into the solar interior. Acoustic shocks due to thick-target heating of the chromosphere are common manifestations of impulsive flares. However, not all such flares release detectable seismic emission, and chromospheric shocks are understood to suffer heavily from radiative losses. Forward modelling supports the hypothesis that sudden, intense continuum emission can contribute significantly to flare acoustic emission by heating the photosphere (radiative back-warming). Changes in the magnetic configurations of sunspots, such as by reconnection, could likewise contribute significantly to flare acoustic emission if sufficiently sudden. However, the actual roles of these and other possible contributors have yet to be realistically quantified in instances in which flare acoustic emission is significant, nor is it known why many large flares are acoustically inactive. More examples are needed of co-spatial and co-temporal observations of seismic sources to explain the presence/absence of seismic activity from flares. *SDO*/HMI will give us high-resolution line-of-sight Doppler maps, continuum and line intensity maps, and vector magnetic maps of nearly all of the flares in SC24. This, together with other space-borne and ground-based facilities, and with ever improving facilities for numerical simulations, offers a most promising and timely insight into this phenomenon.

Acknowledgements I wish to thank the organizers of the BUKS2009 workshop "MHD waves and seismology of the solar atmosphere", it has been especially stimulating. I thank all my discussion colleagues and apologize for any errors and omissions which surely remain in the manuscript. Special thanks go to my collaborator Charles Lindsey who initiated me in the amazing secrets of helioseismic holography, and also for his reading of the manuscript and his suggestions for improvements.

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