Observations of Helioseismic Response to Flare energy-release Events

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Abstract. The energy release in solar flares may cause not only plasma eruptions in the corona and heliosphere, but also may lead to excitation of acoustic wave packets propagating inside the Sun. These waves are observed on the solar surface as ripples propagating from the places where high-energy particles hit the lower chromosphere. Observations of such seismic event (called "sunquakes") provide important information about properties of the high-energy particles accelerated during the energy release events, their interaction with the plasma of the low atmosphere, hydrodynamic and MHD processes in solar flares, and also open perspectives for developing new helioseismic diagnostics. In this paper, I review some recent observational results and discuss an observing program for Solar-B to study such events.

1. Introduction

Wolff (1972) suggested that solar flares may generate acoustic waves traveling through the Sun’s interior. First observations of the seismic waves caused by the X2.6 flare of July 9, 1996 (Kosovichev & Zharkova 1998a), proved these predictions. These observations showed that the source of the seismic response was a strong shock-like compression wave propagating downwards in the photosphere. This wave was observed immediately after the hard X-ray impulse which produced by high-energy electrons hitting the low atmosphere. This led to a suggestion that the seismic response can be explained in terms of so-called “thick-target” model (Brown 1971). In this model, a beam of high-energy electrons heats the solar chromosphere, resulting in evaporation of the upper chromosphere and a strong compression of the lower chromosphere (e.g. Kostiuk & Pikelner 1975; Livshits et al. 1981; Fisher et al. 1985; Kosovichev 1986). This high-pressure compression produces a downward propagating shock wave (Kosovichev 1986) that hits the solar surface and causes sunquakes. This shock, observed in SOHO/MDI Dopplergrams as a localized large-amplitude velocity impulse of about 1 km/s or stronger, represents the initial hydrodynamic impact resulting in the seismic response.

The subsequent observations of solar flares made by the Michelson Doppler Imager (MDI) instrument (Scherrer et al. 1995) on SOHO did not show noticeable sunquake signals even for strong X-class flares until 2003. This search was carried out by Donea & Lindsey (2005) who calculated an “egression” power for high-frequency acoustic waves during the flares (Donea et al. 1999). However, the egression power method can estimate only the integrated power of the seismic waves along an assumed theoretical time-distance relation, and it does not provide physical characteristics of the wave propagation.
Analysis of new observations of the seismic response to solar flares from the SOHO and RHESSI space observatories by Kosovichev (2005) has shown that the sunquakes are most likely caused by the hydrodynamic impact of high-energy electrons accelerated in solar flares, and allowed us to determine the basic properties of the flare-generated seismic waves by investigating their characteristics, such as amplitude, propagation speed and travel times. Of particular interest is the propagation of the acoustic waves through the surrounding regions of strong magnetic fields including sunspots. These new observations allow us to directly investigate the interaction of solar acoustic waves with magnetic field.

2. Observations and Data Analysis

The MDI instrument on SOHO measures motions of the solar surface through the Doppler shift of a photospheric absorption line Ni I 6768 A. The measurements provide images of the line-of-sight velocity of the Sun’s surface every minute with the spatial resolution 2 arcsec per pixel.

Examples of the MDI Dopplergrams obtained during the sunquake events are shown in the two right columns in Figure 1 (grey semitransparent images overlaying darker images of sunspots). There are several types of motions on the solar surface, which contribute to the MDI signal. The largest contributions of about 500 m/s come from the solar convection and stochastic 5-min oscillations excited by convection (they form the noisy granular-like pattern in Fig.1). The amplitude of the flare-generated seismic waves (ring-like features identified in the middle column of Fig.1) rarely exceeds 100 m/s. Thus, because of the strong stochastic motions in the background, these waves are difficult to detect. However, these waves form an almost circular-shape expanding ring, velocity of which is determined by the sound speed inside the Sun and can be calculated from solar models. This property is used to extract the seismic response signal from the noisy data. Because the waves are close to circular the Dopplergrams can be averaged over a range of the azimuthal angle around central points of the initial flare impact. These centers are identified during the flare impulsive phase as strong localized rapidly varying velocity perturbations of about 1 km/s (light and dark localized features in left column of Fig.1). The azimuthally averaged Dopplergrams are plotted as time-distance diagrams (right columns of Fig.1; the averaging angular range in the polar coordinates in indicated at the top), in which the seismic wave forms a continuous ridge corresponding the time-distance relation for acoustic propagating through the solar interior. The slope of this ridge is decreasing with distance, meaning that the waves accelerate. This happens because the seismic waves observed at longer distances travel through the deeper interior of the Sun where the sound speed is higher because of higher plasma temperature. Typically, the ring speed changes from 10 km/s to 100 km/s.

The azimuthally averaged Dopplergrams are plotted as time-distance diagrams (Fig.1c and d; the averaging angular range in the polar coordinates in indicated at the top), in which the seismic wave forms a continuous ridge corresponding the time-distance relation for acoustic propagating through the solar interior. It is remarkable that the time-distance relation of these acoustic waves is very close to the theoretical time-distance relations (dashed curves) for acous-
tic ray paths calculated for the standard solar model. This means that regions of strong magnetic field, such as sunspots, only weakly affect the travel times of the acoustic waves. Also, we do not observe significant change in the amplitude of these as they traveled through the magnetic regions. This suggests that there was no significant absorption or conversion of these waves into other types of MHD waves.

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

Figure 2. A white-light image of active region NOAA 10696 observed on October 28, 2003, and superimposed images of the Doppler signal at the impulsive phase, 11:06 UT, (small-scale light and dark spots show up and down photospheric motions with variations in the MDI signal stronger than 1 km/s), positions of three wave fronts at 11:37 UT, and also locations of the hard X-ray (50-100 keV) sources (white circles) at 11:06 UT, and 2.2 MeV gamma-ray sources (black circles).

Evidently, the X-ray and gamma-ray source are very close to the positions of the seismic sources, but there was no gamma-ray emission near source 3. Also, the gamma emission was not detected for other seismic events. This leads to the conclusion that the origin of the seismic response is the hydrodynamic impact (shock), which is observed in the Doppler signals at 11:06 UT and shows the best correspondence to the central positions of the wave fronts, contrary to the suggestion of Donea & Lindsey (2005) that photospheric heating by high-energy protons is likely to be a major factor. This was verified by calculating the time-distance diagrams for various central positions and various angular sectors. When the central position of a time-distance diagram deviates from the seismic source position this deviation is immediately seen in the diagram as an offset of the time-distance ridge. This approach provides effective source positions for complicated and distributed Doppler signals. A very strong anisotropy of the flare seismic waves was observed for the X10 flare of October 29, 2003 (Fig.3). In
this case, we can see a very narrow (collimated) wave front (Fig.3b) propagating East of the seismic source (white patch in Fig.3a), and the time-distance diagram (Fig.3c) is similar to the other cases.

Figure 3. Observations of the seismic response of X10 flare of October 29, 2003: a) a superposition of MDI white-light images of the active regions and location of the seismic source (white patch) determined from MDI Dopplergram difference during the impulsive phase at 20:43 UT; b) the positions of the very narrow acoustic wave front at 21:10 UT; c) the time-distance diagrams of the flare seismic wave traveling East (180-225 degrees).

The anisotropy of the seismic waves might be related to the properties of magnetic field at the seismic source where high-energy electrons enter the lower chromosphere or to sound-speed inhomogeneities and plasma flows below the surface. In most cases, the largest amplitude was observed in the direction of the expanding flare ribbons. The expanding flare ribbons are observed in hard X-rays, white light, and also in the Dopplergrams, and correspond to the places where energetic electrons precipitate into the lower atmosphere.

The flare of January 15, 2005, of moderate X-ray class, X1.2, but it produced the strongest seismic wave observed so far by SOHO (Fig.1, bottom row). Its amplitude exceeded 100 m/s. This wave had an elliptical shape with the major axis in the SE-NW direction. The elliptical shape corresponds very well to the linear shape of the seismic source extended in this case along the magnetic neutral line. This is illustrated in Figure 4. The left panel shows the grey-scale map the Dopplergram difference at 0:40 UT, in which the long white feature near
Figure 4. Seismic and X-ray sources of the X1.2 flare of January 15, 2005. Left panel shows the Dopplergram difference at 0:40 UT, in which the long white feature near the center corresponds to strong downflows at the seismic source and an image of the hard X-ray source (dark spot). The right panel shows the corresponding MDI magnetogram (light-positive magnetic polarity of the line-of-sight component of magnetic field, black-negative polarity) and an image of the soft X-ray emission (in gray) and contour line of the hard X-ray source.

The high-energy electrons accelerated in the flare (presumably, high in the corona) produced hard X-ray impulse in the lower atmosphere and generated downward propagating shocks which hit the photosphere and generated the seismic waves. This picture corresponds very well to the standard thick target model of solar flares and the models of the hydrodynamic response (e.g. Kostiuk & Pikelner 1975; Livshits et al. 1981; Fisher et al. 1985; Kosovichev 1986). The soft X-ray image indicates this flare was rather compact. One may suggest that the seismic response can be particularly strong in the case of a compact solar flare, but this needs to be confirmed by further observations. Thus, the analysis of sunquakes observed from SOHO/MDI reveals new interesting features: 1) solar flares can produce multiple sunquakes almost simultaneously originating from separate positions (as also found by Donea & Lindsey (2005) for the 10/28/2003 flare); 2) the seismic waves are highly anisotropic, their amplitude can vary significantly with angle; 3) the strongest amplitude is commonly observed in the same direction as the direction of motion of flare ribbons; 4) the wave fronts in most cases have elliptical shape, originating from elongated in one direction initial impulse; 5) the centers of the expanding waves coincide very well with the places of hydrodynamic impacts in MDI Dopplergrams (confirming the initial observation of Kosovichev & Zharkova 1998a), however, not all impact sources produce strong seismic waves; 6) the seismic waves are usually first observed 15–20 min after the initial impact, and reach the highest amplitude 20–30
min after the flare; 7) the seismic waves can travel to large distances exceeding 120 Mm, but, in some cases, decay more rapidly; 8) the fronts of acoustic seismic waves propagate through sunspots without much distortion and significant decay, thus showing no evidence for conversion into other types of MHD waves; 9) the time-distance diagrams for the waves propagating in sunspot regions show only small deviations of the order of 2-3 min from the wave travel times of the quiet Sun; these variations are consistent with the travel time measurements obtained by time-distance helioseismology using the cross-covariance function for random waves (Duvall et al. 1997; Kosovichev et al. 2000).

3. Significance for Solar-B and Suggestions for the Observing Program

Observations of sunquakes provide unique information about the energy release in solar flares, interaction of high-energy particles with the plasma of the lower atmosphere, plasma heating and hydrodynamic processes associated with magnetic energy-release events, formation of shocks and chromospheric evaporation. They also allow us to investigate the interaction of acoustic MHD waves with sunspots, by measuring explicitly propagation of wave fronts through sunspot regions. This opens opportunity for developing new methods of high-resolution helioseismology analysis of flaring active regions.

To investigate these processes I suggest the following observing program for Solar-B:

- **Prior a flare**
  - SOT/FPP vector magnetograms and Doppler velocity (1-min cadence for local helioseismology)

- **Flare impulsive phase (first 20 min after the flare trigger):**
  - SOT/FPP spectrograms
  - XRT/EIS high-cadence flare program

- **Sunquake phase (20 min after the hard X-ray impulse):**
  - SOT/FPP - vector magnetograms and Doppler velocity (30-sec cadence)

This observing program will allow us to investigate prior the flares the evolution of the magnetic field of active regions and subphotospheric dynamics that drives changes in the magnetic structure, and may be significant for the trigger mechanism of the magnetic energy release. During the impulsive phase, it is important to obtain spectrograms of the region close to the energy release site. This will allow us to investigate the rapid variations of the magnetic field and changes in the magnetic configuration associated with magnetic reconnection in the upper atmosphere corona and energy release. The spectrogram will also provide diagnostics for the strong mass motions and shocks in the lower chromosphere, which provide energy and momentum transport. It is also important
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to investigate changes in thermodynamic properties, density and temperature of the photospheric, chromospheric and coronal plasma. The expanding seismic waves usually become visible 20 min after the start of the impulsive phase. To observe these waves it is necessary to switch to the filtergram mode (NFI) and obtain 30-sec Dopplergrams. These waves have higher frequencies than the normal 5-min oscillations. Thus, they should be observed with 30 sec cadence. These observations should continue for about an hour.

It will be very beneficial to run this observing program jointly with other space missions, in particular, RHESSI, which provides critical hard X-ray images, and SOHO/MDI full-disk Dopplergrams and magnetograms. The ground-based Doppler and magnetic field observations from the GONG+ network are also very important.

References

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