SUNQUAKE SOURCES AND WAVE PROPAGATION

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ABSTRACT

Solar flares generate sunquakes observed as ripples on the solar surface. This helioseismic response to solar flares is caused by energetic particles penetrating into the lower atmosphere. The sunquake sources are observed directly in the MDI Dopplergrams as localized high-velocity impulses. The seismic sources are typically located in arc ribbons and correlate very well with sources of hard X-ray emission produced by high-energy electrons and observed from RHESSI. Detailed analysis of SOHO/MDI data showed that the structure of sunquake sources can be quite complicated in space and time. The analysis of several sunquake events in 2003-5 revealed new important features such as the strong anisotropy and ellipticity of the seismic wave fronts, and it also showed much smaller than expected distortion of the fronts when the waves propagate through sunspots. The helioseismic waves tend to have the greatest amplitude in the direction of expansion of the arc ribbons. This phenomenon is somewhat similar to the fault rupture effect in earthquakes, and can be explained by theoretical calculations of sunquake waves. In some cases, the wave anisotropy can be also caused by subsurface structures and organized flows. Investigation of sunquakes provides new insight into the physics of solar flares and new means for local helioseismic diagnostics.

Key words: Sun: flares, Sun: helioseismology, Sun: oscillations, sunspots.

1. INTRODUCTION

It was suggested long ago [25] that solar flares may cause acoustic waves traveling through the Sun’s interior, similar to the seismic waves in the Earth. Because the sound speed increases with depth, the waves are reflected in the deep layers of the Sun and appear back on the surface, forming expanding rings of the surface displacement. Theoretical modeling [12] predicted that the speed of the expanding seismic waves increases with distance because the distant waves propagate into the deeper interior where the sound speed is higher. First observations of the seismic waves caused by the X2.6 flare of 9 July, 1996, [13] proved these predictions. These observations also showed that the source of the seismic response was a strong shock-like compression wave propagating downwards in the photosphere. This wave was observed immediately after the hard X-ray impulse which produced by high-energy electrons hitting the low atmosphere. This led to a suggestion that the seismic response can be explained in terms of so-called “thick-target” models. In these models, a beam of high-energy particles heats the solar chromosphere, resulting in evaporation of the upper chromosphere and a strong compression of the lower chromosphere [16, 17, 6, 10]. This high-pressure compression produces a downward-propagating shock wave [10] that hits the solar surface and causes sunquakes (Fig. 1). This shock observed in SOHO/MDI Dopplergrams as a localized large-amplitude velocity impulse of about one km/s or stronger, represents the initial hydrodynamic impact resulting in the seismic response. In addition, it was found that the seismic disturbance had a significant quadrupole component [14]. However, the seismic wave front was almost circular.

Subsequent observations of solar flares made by the Michelson Doppler Imager (MDI) instrument on the NASA-ESA mission SOHO did not show noticeable sunquake signals even for strong X-class flares. This search was carried out by calculating an “egression” power for high-frequency acoustic waves during the flares [3]. It became clear that sunquakes are a rather rare phenomenon on the Sun, which occur only under some special conditions. Surprisingly, seven years later several flares did show strong “egression” signals indicating new potential sunquakes [? ]. Of course, detection of sunquakes depends on their amplitude relative to the background solar noise. Presumably, all flares have seismic consequences at some level, but if the wave amplitude is not high enough they may get lost in the background noise.

It is interesting to note that the flare of 9 July, 1996, was the last strong flare of the previous solar activity cycle, and the new strong sunquake events are observed in the declining phase of the current activity cycle after the maximum of 2000–2001 (Fig. 2). It appears that during the rising phase of the solar cycle and during its peak, the solar flares are rather a “superfluous” coronal phenomenon not affecting much the solar surface and interior. This could happen if the topology of the magnetic field of solar active regions which produce flares changes in such a way that the magnetic energy is released at lower altitudes in the declining phase of the solar cycle than in the
Figure 1. Schematic representation of the thick-target model and sunquake source. Accelerated high in the corona high-energy electrons heat the upper chromosphere resulting in chromospheric evaporation and downward propagating shock, which causes sunquake.

Figure 2. The sunspot number (blue) and the distribution of solar flares of various X-ray class during the past three solar cycles (small cycles) (courtesy of Dave Hathaway). The large red circles show the strong sunquake events observed from SOHO/MDI in 1996-2005.

In this paper, I present new analysis of the seismic responses to solar flares from the MDI data, and discuss which particles electrons or ions cause the hydrodynamic and seismic response, and also suggest a mechanism explaining the anisotropy of the seismic waves.

2. RESULTS OF ANALYSIS OF SOHO/MDI AND RHESSI DATA

2.1. Observations and data analysis procedure

The MDI instrument on SOHO measures motions of the solar surface through the Doppler shift of a photospheric absorption line: Ni I $6768\AA$. The measurements provide images of the line-of-sight velocity of the Sun's surface every minute with a spatial resolution of two arcsec per pixel. Examples of the MDI Dopplergrams obtained during four sunquake events are shown in the two right columns in Figure 3 (grey semitransparent images overlaying color images of sunspots).

There are several types of motions on the solar surface, which contribute to the MDI signal. The largest contributions of about 500 m s$^{-1}$ come from solar convection and five-minute oscillations excited by convection (they form the noisy granular-like pattern in Figure 3). The amplitude of the flare-generated seismic waves (ring-like features identified in the middle column of Figure 1) rarely exceeds 100 m s$^{-1}$. Thus, because of the strong stochastic motions in the background, these waves are difficult to detect. However, these waves form an almost circular-shaped expanding ring, the velocity of which is determined by the sound speed inside the Sun and which can be calculated from solar models. The regularity of the wave front can be 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 azimuthal angle around the 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 one km s$^{-1}$ (light and dark features in left column of Figure 3).

The azimuthally-averaged Dopplergrams are plotted as time-distance propagation diagrams (right columns of Figure 3; the averaging angular range in the polar coordinates is indicated at the top), in which the seismic wave forms a continuous ridge corresponding to the time-distance relation for acoustic waves propagating through the solar interior. The slope of this ridge is decreasing with distance, meaning that the waves accelerate. This
Figure 3. Observations of the seismic response of the Sun ("sunquakes") to four solar flares: a) X17 of 28 October, 2003, b) X10 of October 29, 2003, c) X3 of 16 July, 2004, and d) X1 flare of 15 January, 2005. The left panels show a superposition of MDI white-light images of the active regions and locations of the sources of the seismic waves determined from MDI Dopplergrams, the middle column shows the seismic waves, and the right panels show the time-distance diagrams of these events. The thin yellow curves in the right panels represent a theoretical time-distance relation for helioseismic waves for a standard solar model.
Figure 4. A white-light image of active region NOAA 10696 observed on 28 October, 2003, and superimposed images of the Doppler signal at the impulsive phase, 11:06 UT, (blue and yellow spots show up and down photospheric motions with variations in the MDI signal stronger than 1 km s$^{-1}$), positions of three wave fronts at 11:37 UT, and also locations of the hard X-ray (50–100 keV) sources (yellow circles) at 11:06 UT, and 2.2 MeV $\gamma$-ray sources (green circles).

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 the higher plasma temperature. Typically, the ring speed changes from 10 km s$^{-1}$ to 100 km s$^{-1}$.

Because of the high solar noise, the seismic waves are not easily seen on individual Dopplergrams. They are much more easily recognized in Dopplergram movies as expanding wave fronts. These movies together with a PowerPoint presentation are available at http://quake.stanford.edu/~sasha/SUNQUAKES.

The typical oscillation frequency of the flare waves is higher than the mean frequency of the background fluctuations (four–five mHz vs. three mHz). Therefore, frequency filtering centered at five or six mHz helps to increase the signal-to-noise ratio. In most cases, a frequency filter centered at six mHz with the width of two mHz is used, and, in addition, a difference filter for consecutive images is applied.

2.2. Basic properties of sunquakes

Localized Doppler perturbations during the flare impulsive phase, similar to that shown in the Figure 3 (left panels) and associated with precipitation of high-energy particles are observed in many flares, particularly X-class. However, in most cases the hydrodynamic impact of the lower atmosphere and, thus, the seismic response appear to be weak and may get lost in the background noise.

Figure 3 presents results for the strongest events, observed on 28 and 29 October, 2003; 16 July, 2004, and 15 January, 2005. The first flare of 28 October, 2003, was one of the strongest ever observed, with the soft X-ray class X17. It is interesting that the flares of 16 July, 2004, and 15 January, 2005, had much weaker soft X-ray emission, but produced higher amplitude seismic waves than the X17 flare.

The sunquake images in Figure 3 reveal new interesting features of the seismic response [11]: 1) the seismic waves are highly anisotropic, their amplitude can vary significantly with angle; 2) the strongest amplitude is commonly observed in the same direction as the direction of motion of flare ribbons; 3) the wave fronts can deviate from the circular shape and have approximately elliptical shape, originating from an initial impulse elongated in one direction; 4) the centers of the expanding waves coincide very well with the places of hydrodynamic impacts in MDI Dopplergrams, confirming the initial observation [13], however, not all impact sources produce strong seismic waves; 5) 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; 6) the seismic waves can travel to large distances exceeding 120 Mm, but, in some cases, decay more rapidly; 7) the fronts of acoustic seismic waves propagate through sunspots without much distortion or significant decay, thus showing no evidence for conversion into other types of MHD waves; 8) the time-distance propagation diagrams for the waves traveling through sunspot regions show only small deviations of the order of two to three minutes 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 [5, 15].

2.3. The source of sunquakes: high-energy electrons or protons?

For two flares, X17 flare of 28 October, 2003, and X5.6 flare 23 July, 2002, X-ray and $\gamma$-ray data are available for analysis. The RHESSI image reconstruction software was used to obtain locations of the X-ray sources in the X17 flares and to compare with the MDI Doppler measurements of the hydrodynamic impulses and seismic responses. The positions of hard X-ray sources for the X5.6 flare, and the positions of the $\gamma$-ray sources for both flare were taken from [7, 8, 9]. Hard X-ray emission is caused by high-energy electron, and the $\gamma$-ray emission is caused by high-energy protons.

Figure 4 shows a white-light image of the flaring active region (NOAA 10696) and the superimposed images of the Doppler signal in the impulsive phase, 11:06 UT, (blue and yellow spots show up and down photospheric motions with variations in the MDI signal stronger than...
one km s\textsuperscript{-1}), positions of three wave fronts at 11:37 UT, and also locations of the hard X-ray (50–100 keV) sources (yellow circles) at 11:06 UT, reconstructed from the RHESSI data using the maximum entropy image reconstruction algorithm, provided with the RHESSI data analysis software. In addition, this figure shows 2.2 MeV gamma-ray sources (green circles), averaged for the whole flare duration [8, 9].

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, \( \gamma \)-emission was not detected for other seismic events. However, the strong photospheric motions observed in the Doppler signals at 11:06 UT show the best correspondence to the central positions of the wave fronts. This leads us to the conclusion that the origin of the seismic response is the hydrodynamic impact caused by high-energy electrons.

This is convincingly confirmed by observations of the X5.6 flare of July 23, 2002. In this flare, hard X-ray and \( \gamma \)-ray sources were spatially separated, thus, providing an opportunity to investigate the hydrodynamic and seismic effects for these sources separately. Figure 5 (left panel) shows the positions of hard X-ray sources (blue) and the \( \gamma \)-ray source (red in the MDI magnetogram (gray-scale background). The analysis of MDI Dopplergrams shows that a strong hydrodynamic response was only in the region of hard X-ray sources. There was no detectable variations associated with the \( \gamma \)-ray source. Also, the seismic waves are observed only from the hard X-ray source area. In this case, the signal of the seismic waves is weak because the flare was close to the limb. These seismic are detected using the time-distance propagation diagrams shown in the right panel of Fig. 5.

Thus, we conclude that the sources of sunquakes are high-energy electrons, and not protons (contrary to the suggestion in [4]).

2.4. The cause of anisotropy of sunquakes

Perhaps, the most significant new feature is the strong anisotropy of the seismic response. This is evident from the wavefront images shown in the middle panels of Figures 3a–d. The anisotropy seemed to be particularly pronounced for the 29 October, 2003, flare when only a very narrow part of the wave front, propagating to the East, could be identified in individual Doppler images (Figure 3b, middle panel). Such significant changes of the wave amplitude with direction can be caused by variations in the wave speed due to temperature and magnetic field structures, direction of the initial impact, and, perhaps, most significantly by the seismic source motion.

In the case of the 28 October, 2003 (X17) flare, it was particularly evident that the sunquake waves had the greatest amplitude in the direction of motion of the initial impact source’s locations of the high-energy particle precipitation. The places of the initial impact of high-energy particles in the magnetic loop footpoints form the expanding flare ribbons. The position of the impact place of the high-energy electrons is best seen in MDI magnetograms. In these place, the magnetic field measurements
are strongly perturbed, and often show the sign opposite to the background field. The position and motion of source 2 of the X17 flare of October 28, 2003, are clearly seen in Figure 6. Figure 7 shows a result of a model calculations of acoustic waves excited by a moving point source. This shows that the wave anisotropy may be quite strong due to the interference effect.

3. DISCUSSION

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 (Fig. 1) qualitatively corresponds very well to the standard thick target model of solar flares [24] and the models of the hydrodynamic response [16, 17, 6, 10]. The soft X-ray image indicates that 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. Also, detailed radiative hydrodynamic simulations of the particular events are required to confirm the mechanism of sunquakes.
The new observations from SOHO and RHESSI provide unique information about the interaction of the high-energy particles accelerated in solar flares with solar plasma and the dynamics of the solar atmosphere during solar flares. These data also provide unique information about the interaction of acoustic MHD waves with sunspots, showing explicitly propagation of wave fronts through sunspot regions.

The new observed properties, in particular, the strong anisotropy of the acoustic wave front, challenge the current theoretical models of sunquakes [12, 18, 19, 20]. These models considered concentrated impulsive perturbations of pressure and momentum (which can be expected if the hydrodynamic impact is localized and predominantly normal to the solar surface) and predicted an isotropic seismic response. The anisotropy of the sunquakes is probably related to a complex sequence of energy-release events and more complex geometry of magnetic fields guiding the direction of the high-energy particles and plasma motion in the atmosphere.

In particular, the anisotropy can be caused by the constructive interference of the seismic waves if the flare impact is not localized in time and space. Such a moving seismic source can be produced by a series of consecutive hydrodynamic events at the footpoints of neighboring magnetic flux tubes. The fact that the waves predominantly propagate in the direction of the expanding flare ribbons supports this suggestion. This phenomenon is somewhat similar to that well-known in terrestrial seismology of the anisotropy of seismic waves when the earthquake rupture propagates along the fault.

In the solar case, the motion of the seismic source (observed as flare ribbons) can be caused by a sequence of magnetic reconnection events in the upper atmosphere. In a standard model of solar flares [23, 22], the reconnection region during the impulsive phase is moving up along the cusp-shaped loops and increasing the distance between the footpoints of magnetic loops, where the energetic particles hit the lower atmosphere. However, in reality the geometry and dynamics of the flare ribbons is more complicated than in the 2D reconnection models. Sometimes, observations show that the hard X-ray sources show motions along the flare ribbons, not in the direction of their separation. Thus, detailed modeling of the complex flare seismic sources and waves can provide new insight into the processes of flare energy release and particle acceleration.

Another interesting result of this investigation is the apparently small effect of the sunspot regions with strong magnetic fields on the wave propagation. The power of five-minute oscillations in sunspots is reduced by more than 50%, which is usually attributed to absorption of acoustic waves in magnetic regions and their transformation into various MHD waves escaping along the field lines [1, 2]. Our observations indicate that the wave absorption and transformation in magnetic regions is probably much weaker than was assumed before. The weak interaction of the seismic waves with sunspots can be explained by the deep propagation of these waves through the subsurface sunspot regions where the magnetic pressure is much smaller than the gas pressure. The acoustic waves on the Sun do not propagate horizontally along the surface, but they travel through the deep interior and only appear at the surface. The penetration depth of these waves depends on the travel distance. Perhaps, only for the shortest distances (smallest depths) magnetic effects may play dominant role. The interaction of sunquakes with sunspots requires further analysis.

Thus, observations and analysis of sunquake events opens opportunities for developing new methods of helioseismic analysis of flaring active regions, similar to the methods of Earth-quake seismology, and for better understanding of the energy release and transport in solar flares.

REFERENCES


