THE CAUSE OF PHOTOSPHERIC AND HELIOSEISMIC RESPONSES TO SOLAR FLARES: HIGH-ENERGY ELECTRONS OR PROTONS?

A. G. Kosovichev
W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305

Received 2007 July 22; accepted 2007 October 1; published 2007 October 17

ABSTRACT

Analysis of the hydrodynamic and helioseismic effects in the photosphere during the solar flare of 2002 July 23, observed by MDI/SOHO, and high-energy images from RHESSI show that these effects are closely associated with sources of the hard X-ray emission but that no such effects existed in the centroid region of the flare’s gamma-ray emission. These results demonstrate that, contrary to expectations, these hydrodynamic and helioseismic responses (“sunquakes”) are more likely to be caused by accelerated electrons than by high-energy protons. A series of multiple impulses of high-energy electrons form a hydrodynamic source that is moving in the photosphere at supersonic speed. This moving source plays a critical role in the formation of the anisotropic wave front of sunquakes.

Subject headings: Sun: flares — Sun: oscillations — Sun: X-rays, gamma rays

1. INTRODUCTION

“Sunquakes,” helioseismic responses to solar flares, are caused by strong localized hydrodynamic impacts in the photosphere during a flare’s impulsive phase. The helioseismic waves are observed directly as expanding circular-shaped ripples in the Dopplergrams from the Michelson Doppler Imager (MDI) on the Solar and Heliospheric Observatory (SOHO); these ripples are also observed as a characteristic ridge in time-distance diagrams (Kosovichev & Zharkova 1998; Kosovichev 2006a) or, indirectly, by calculating the integrated acoustic emission (Donea et al. 1999; Donea & Lindsey 2005). Solar flares are sources of high-temperature plasma and strong hydrodynamic motions in the solar atmosphere. Perhaps, in all flares, such perturbations generate acoustic waves that travel through the interior. However, only in some flares is the impact sufficiently localized and strong to produce seismic waves with an amplitude above the convection noise level. It has been established in the 1996 July 9 flare observations (Kosovichev & Zharkova 1998) that the hydrodynamic impact follows the hard X-ray (HXR) flux impulse and, hence, the impact of high-energy electrons. Nevertheless, a common paradigm is that the sunquake events are caused by accelerated protons, because protons carry more momentum and penetrate deeper into the solar atmosphere than do electrons, which lose most of their energy in the upper chromosphere. This paradigm is not easy to test because the gamma-ray emission, which indicates the presence of high-energy protons, is rarely observed.

In a large X17 flare on 2002 October 28, the gamma-ray emission observed by RHESSI was located close to the hard X-ray emission and was also located in two of the three places where photospheric impacts (sunquake sources) were observed (Kosovichev 2006a). Because the hard X-ray and gamma-ray emissions were located so close to each other, these observations could not exclude the possibility of proton or mixed electron-proton impacts (Zharkova & Zharkov 2007).

However, in one event, the X4.8 flare of 2002 July 23, the hard X-ray and gamma-ray emissions were significantly separated from each other. The centroid of the γ-ray 2.233 MeV neutron-capture emission was found to be displaced by 20′′ ± 6′′ (with 5 σ confidence) from that of the 0.3–0.5 MeV X-ray emission, which implied a difference in acceleration and/or propagation between the accelerated electrons and ions (Hurford et al. 2003). Therefore, this flare provides us with a unique opportunity to investigate the photospheric and helioseismic responses separately for high-energy electrons and protons. In this Letter, I present results of the analysis of the relationship between the hard X-ray and gamma-ray emissions and the hydrodynamic and seismic signals in the photosphere, using data from RHESSI (Lin et al. 2002) and MDI/SOHO (Scherrer et al. 1995). RHESSI provides X-ray/gamma-ray imaging spectroscopy from 3 keV to 17 MeV with an angular resolution of 2.3′–3′ (35′ at gamma-ray energies) over the full Sun. MDI measures the Doppler velocity and the line-of-sight magnetic field of the photospheric plasma every minute with a resolution of 2″ per pixel over the full Sun.

2. ANALYSIS OF MDI/SOHO AND RHESSI DATA

The X4.7 flare of 2002 July 23 was the first flare for which gamma-ray images were obtained (Hurford et al. 2003). Other examples of flares with RHESSI gamma-ray images are given by Hurford et al. (2006). The properties of the gamma-ray and hard X-ray emissions, as well as other aspects of the 2002 July 23, flare, are discussed in the RHESSI special issue of ApJ Letters (2003, v595n2). The RHESSI observations revealed three hard X-ray sources and one gamma-ray source. Their positions in the MDI magnetogram are shown in Figure 1a (Krucker et al. 2003). The hard X-ray sources (labeled f1, f2, and f3) were located on both sides of the magnetic neutral line. The morphology of the gamma-ray emission was not resolved, but it could not have been more than 1′ (FWHM) in extent, and its centroid was 20′′ ± 6′′ south of the centroid of the hard X-ray sources and about 30′′ from the f1 source.

The MDI Dopplergrams show strong impulsive variations close to the hard X-ray sources, but none are visible in the region of the gamma-ray source centroid or anywhere outside the hard X-ray sources. Figure 1b shows the positions of the impulsive Doppler velocity signals in the photosphere, during the flare impulsive phase between 00:27 and 00:36 UT of 2002 July 23. This flare was rather close to the limb (coordinates of the flare sources are given in Fig. 1); the distance from the disk center was approximately 70′. Thus, if the angle between the magnetic field lines, which direct the plasma motion at the footpoints (Fig. 2), and the line of sight changes sign, then it is possible that the projection effect contributed to the opposite sign of the Doppler shift across the neutral line. However, there might be other reasons for the
opposite velocity sign related to flare hydrodynamics that should be explored.

The strongest Doppler signal, corresponding to a downward plasma motion, appeared near the X-ray source, \( f_1 \). Its position moved in the northern direction during the impulsive phase. This motion is discussed in more detail in the next section. The time dependence of the velocity signal at source \( f_1 \) corresponds very well (with the correlation coefficient of 0.8) to the total hard X-ray flux in the 50–300 keV range (Figs. 3c and 3d). Because of the time it takes for neutrons to thermalize (Murphy et al. 2003), the gamma-ray emission (Fig. 3e) is delayed by \( \sim 100 \text{ s} \).

The helioseismic waves are best visible at frequencies of about 5–6 mHz. To search for these waves, the Dopplergrams had to be remapped into the heliographic coordinates, tracked to remove the displacement caused by the solar rotation, and then filtered using a bandpass filter centered at 5.5 mHz with a FWHM of 2 mHz. Then the filtered Dopplergrams had to be remapped into polar coordinates, centered at various points (including all hard X-ray sources and the gamma-ray source centroid region), and averaged azimuthally in several angular sectors. The averaged signals are plotted as a function of the radial distance and time, constituting time-distance propagation diagrams. The diagrams were inspected for an elongated characteristic ridgelike structure, which is caused by helioseismic waves, as predicted theoretically (Kosovichev & Zharkova 1995), and observed in other sunquake events (Kosovichev & Zharkova 1998; Kosovichev 2006a). In this case, a rather weak ridge appeared only in the propagation diagram, which was centered in the region of the strongest impulsive Doppler signal, at the \( f_1 \) source, and averaged in the northwest quadrant. It can be identified in Figure 1c at distances between 20 and 40 Mm, just above the theoretical time-distance relation for helioseismic acoustic waves. The traveling wave front can be seen in the movie of the frequency-filtered Dopplergrams. The observed signal is rather weak, because a flare generates high-frequency acoustic waves in which the plasma velocity is predominantly vertical (Kosovichev & Zharkova 1995) and in which its line-of-sight projection is reduced by almost 2/3 due to the close-to-limb location. The amplitude of the line-of-sight plasma velocity in this wave was about 20 m s\(^{-1}\). For the other central positions (including X-ray sources \( f_2 \) and \( f_3 \), and X-ray and gamma-ray centroids) and sectors, the seismic waves were not detected. This analysis puts the source of the seismic wave within the lower red part of the Doppler source \( f_1 \) in Figure 1b. The start time, estimated from the theoretical time-distance relation in the ray approximation, is 00:28–00:30 UT. It is interesting to note that X-ray source \( f_2 \) is marginally stronger than X-ray source \( f_1 \) but that the impulsive Doppler signal is stronger in the \( f_1 \) position than in the \( f_2 \) position.

The absence of any significant photospheric signal in the region of the gamma-ray centroid and the close correlation between the hard X-ray flux source and the hydrodynamic and helioseismic responses indicate that the source of the helioseismic waves is associated with the high-energy electrons and not with the high-energy protons. We note that, although the RHESSI data do not exclude the presence of protons in the footpoints of the hard X-ray sources, for this conclusion it is
important to note that the proton flux in the gamma-ray centroid area was not weaker than that in the HRX sources. This assumption is supported by the RHESSI data. For further studies, it would be helpful to put precise limits on the proton flux at the X-ray footpoints and to estimate the relative energetics of protons and electrons from RHESSI data.

3. MOVING HARD X-RAY AND SUNQUAKE SOURCES

A characteristic feature of the seismic response in this flare and in several others (Kosovichev 2006a, 2006b) is the anisotropy of the wave front; the observed wave amplitude is much stronger in one direction than in the others. In particular, the seismic waves excited during the 2003 October 28 flare had the greatest amplitude in the direction of the expanding flare ribbons. The wave anisotropy was attributed to the moving source of the hydrodynamic impact, which is located in the flare ribbons (Kosovichev 2006a, 2006c). The motion of flare ribbons is often interpreted as the result of the magnetic reconnection processes in the corona. Higher magnetic loops are required for the reconnection region to move up, and these higher magnetic loops have footpoints that are farther apart. Of course, there might be other reasons for the anisotropy of the wave front, such as inhomogeneities in temperature, magnetic field, and plasma flows. However, the source motion seems to be quite important.

It is interesting to note that, in the case of the 2002 July 23 flare, the seismic source identified in MDI Dopplergrams as a place of strong Doppler shifts in region f1 was moving mostly along the flare ribbon, and consequently the seismic wave had the strongest amplitude in the direction closest to the direction of the source motion (but not precisely; in this case, in addition to the other factors, stronger foreshortening on the east side might have contributed to the signal loss in the northeast quarter). The Doppler source motion nicely corresponds to the motion of the hard X-ray source discovered by Krucker et al. (2003). Figure 4a shows the evolution of the hard X-ray sources’ positions on the magnetogram (see f1, f2 and f3), and Figure 4b shows the propagation diagrams determined by Krucker et al. (2003) for these sources. From the top panel of Figure 4b, the hard X-ray source, f1, traveled approximately 7 Mm in 5 minutes; this corresponds to the mean speed of approximately 20–25 km s\(^{-1}\). According to Krucker et al. (2003), the maximum speed reached was 50 km s\(^{-1}\).

Using the MDI Dopplergrams, Krucker et al. (2003) constructed a similar time-distance propagation diagram for the plasma photospheric velocity along the line of motion of source f1. Figure 4c shows the Doppler velocity along a 2 pixel–wide strip along this line. This diagram shows that the evolution of the hydrodynamic impact source is very similar to the evolution of the hard X-ray source (top panel in Fig. 4b). The mean speed of the hydrodynamic source was also about 20–25 km s\(^{-1}\).

Therefore, we conclude that the seismic wave was generated not by a single impulse, as was suggested in the sunquake models of Kosovichev & Zharkova (1995), Medrek et al. (2000), and Podesta (2005), but by a series of impulses, which produce the hydrodynamic source moving on the solar surface at supersonic speed. The seismic

![Image](image-url)
effect of the moving source can be easily calculated by convolving
Green’s function of the seismic wave (the wave signal from a point
δ-function–type source), G(x = x, y = y, t), with a moving source
function, S(x = Vt, y = Vt, t). The results of these calculations
are illustrated in Figure 5, which shows the wave front for a source
moving along the x-axis at a speed of 25 km s⁻¹. The strength of
this source varied with time as a Gaussian with a FWHM of 3
minutes (it is shown as black diamonds in Fig. 5). Green’s function
was calculated by the use of the standard mode summation method
(Kosovichev & Zharkova 1995). The strong anisotropy of the seismic
wave is evident. Curiously, this effect is quite similar to the
anisotropy of seismic waves on Earth, when an earthquake rupture
moves along the fault (e.g., Ben-Menahem 1962). Thus, taking into
account the effect of multiple impulses of accelerated electrons and
the effect of the moving source is very important for sunquake
theories. These effects will be discussed in more detail in future
publications.

4. DISCUSSION

The analysis of RHESSI X-ray and gamma-ray images and
of MDI/SOHO Dopplergrams of the 2002 July 23 X4.8 solar
flare revealed that the hydrodynamic and seismic effects were
closely associated with the sources of hard X-ray emission,
both spatially and temporally, but it also showed that no sig-
nificant responses existed in the centroid region of the flare’s
gamma-ray emission. Because this flare was one of strongest
gamma flares, and because the hard X-ray and gamma-ray
sources were separated, these observations show that the ac-
celerated protons were unlikely to be the sources of the hy-
drodynamic responses or sunquakes. Furthermore, the detailed
analysis of the dynamics of sunquake sources, which is found
in this Letter and in the paper by Kosovichev (2006a), reveals
their close association with expanding flare ribbons, with the
rapid HXR source motion along the ribbons, and, thus, with
the magnetic reconnection process. The fast motion of these
sources results in the strong anisotropy of the seismic waves,
which is clearly observed in the MDI data.

The general picture that comes from the analysis of MDI/SOHO
and RHESSI data is consistent with the previously developed hy-
drodynamic thick-target model, which is illustrated in Figure 2
(Kostiuk & Pikelner 1975; Livshits et al. 1981; Fisher et al. 1985;
Kosovichev 1986). In this model, high-energy electrons heat the
upper chromosphere to high temperatures, generating a high-pres-
sure region, the expansion of which causes the evaporation of the
chromospheric plasma and a high-compression shock. The shock
reaches the photosphere and excites the seismic waves. However,
the new results show that it is important to include the effect of
the multiple impact and the effect of the moving source in the
thick-target and sunquake models.

The photospheric and helioseismic effects observed during the
impulsive phase of solar flares are closely related to the processes
of acceleration and propagation of electrons and ions, and they
may provide new important information about these processes.

REFERENCES

Ben-Menahem, A. 1962, J. Geophys. Res., 67, 345
Donea, A.-C., Braun, D. C., & Lindsey, C. 1999, ApJ, 513, L143
Donea, A.-C., & Lindsey, C. 2005, ApJ, 630, 1168
Fisher, G. H., Canfield, R. C., & McClymont, A. N. 1985, ApJ, 289, 434
Hurford, G. J., Krucker, S., Lin, R. P., Schwartz, R. A., Share, G. H., & Smith,
D. M. 2006, ApJ, 644, L93
Hurford, G. J., Schwartz, R. A., Krucker, S., Lin, R. P., Smith, D. M., &
Vilmer, N. 2003, ApJ, 595, L77
Kosovichev, A. G. 1986, Bull. Crimean Astrophys. Obs., 75, 6
———. 2006a, Sol. Phys., 238, 1
———. 2006b, in ASP Conf. Ser. 354, Solar MHD Theory and Observations:
A High Spatial Resolution Perspective, ed. J. Leibacher, R. F. Stein, &
H. Uitenbroek (San Francisco: ASP), 154
———. 2006c, in Proc. SOHO 18/GONG 2006/HELAS I, Beyond the Spherical
Skin, ed. K. Fletcher (ESA SP-624: Paris: ESA), 134.1
Kosovichev, A. G., & Zharkova, V. V., 1995, in Proc. Fourth SOHO Workshop,
Helioseismology, ed. J. T. Hoeksema et al. (Paris: ESA), 341
———. 1998, Nature, 393, 317
Kostiuk, N. D., & Pikelner, S. B. 1975, Soviet Astron., 18, 590
Krucker, S., Hurford, G. J., & Lin, R. P. 2003, ApJ, 595, L103
Lin, R. P., et al. 2002, Sol. Phys., 210, 3
Livshits, M. A., Badalian, O. G., Kosovichev, A. G., & Katsova, M. M. 1981,
Sol. Phys., 73, 269
Medrek, M., Murawski, K., & Nakariakov, V. 2000, Acta Astron., 50, 405
Murphy, R. J., Share, G. H., Hua, X.-M., Lin, R. P., Smith, D. M., & Schwartz,
R. A. 2003, ApJ, 595, L93
Podesta, J. J. 2005, Sol. Phys., 232, 1
Scherrer, P. H., et al. 1995, Sol. Phys., 162, 129
Zharkova, V. V., & Zharkov, S. I. 2007, ApJ, 664, 573