X-Ray Flare Quakes the Sun

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Solar flares are the strongest localized seismic disturbances on the solar surface. During the impulsive phase a high-energy electron beam heats the chromosphere, resulting in explosive evaporation of chromospheric plasma at supersonic velocities. This upward motion is balanced by a downward recoil in the lower part of the chromosphere that excites propagating waves in the solar interior. On the solar surface the outgoing circular flare waves resemble ripples from a pebble thrown into a pond. We report on the first observation of the seismic waves from a solar flare from the Michelson Doppler Imager (MDI)[1] on board Solar and Heliospheric Observatory (SOHO) on 9 July 1996, and compare the results with a theoretical model. This seismic wave propagated to at least 120,000 km from the flare epicenter with an averaged speed of about 50 km/s on the solar surface and was about 3 km high. The discovery of flare seismic waves is important for understanding mechanisms of flare energy and momentum transport and for studying the subphotospheric structure of active regions.

Solar activity associated with sunspots and flares is currently at the minimum of its 11-year cycle. The flare of 9 July, which quaked the Sun, was the only significant X-ray flare observed in 1996. This was a fairly moderate flare classified as X2.6/1B with the corresponding X-ray flux of 0.26 erg cm^{-2} s^{-1}. When the solar activity is near its maximum, observations of flares with several times this energy are not uncommon. More energetic flares are expected to quake the Sun stronger. However, the previous attempts[3,4] to detect the seismic signal of solar flares from ground-based observations were inconclusive.

The X-ray impulse of this flare detected by BATSE (Burst and Transient Source Experiment)[2] on board the Compton Gamma Ray Observatory began to increase at 09:07:49 UT and reached a sharp maximum at 09:09:40 (Fig. 1). The magnetic field measurements from MDI show that the flare energy release was associated with emerging flux of opposite polarity in the active region NOAA 7978 a few hours prior the flare. The flare occurred when MDI was operating in the full-disk mode taking 1024x1024 pixel 60-sec averaged Doppler velocity observations every minute. Analyzing the MDI Dopplergrams, we have detected strong localized upward and downward mass flows during the X-ray impulse. These flows shown in Fig.2a occupied 2 or 3 pixels of the solar image on the CCD, which corresponds to a linear size of about 3-5 Mm. The velocity impulse (Fig.1) was almost as sharp as one in the X-ray flux. However, the maximum velocity of ~ 1.5 km s^{-1} was observed approximately 1 min after the X-ray maximum, at 09:11:00. This time delay is consistent with theoretical predictions based on the so-called 'thick-target' model of solar flares.[5–8] These models predict a strong downward propagating shock originated after a high-energy electron beam heated the 'target' - cool chromospheric layers. This shock causes then the seismic impact. It is likely that the actual velocity impulse is smoothed in the 60 s-average Dopplergrams, and that in reality it was significantly stronger and sharper. We use the parameters of the velocity impulse for estimating the momentum of the flare impact.

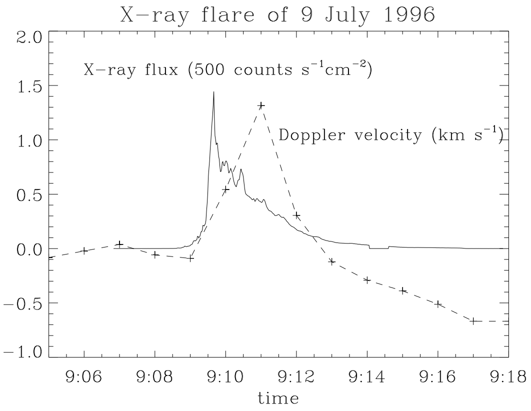

Figure 1: The 1.024-sec averages of the X-ray flux in the energy range 25-100 keV of the solar flare of 96/07/09 from the BATSE flare monitor (solid curve), and the 1-min averages of the Doppler velocity of the downflowing plasma in the flare core from the MDI (dashed curve).

By simply displaying the MDI Dopplergrams in sequence, we have detected a circular wave packet propagating from the flare. The wave is first detected at about 09:30, approximately 20 min after the flare, at a distance of $\approx$ 18 Mm from the flare site. The wave is clearly observed in the sequence of Dopplergrams for about 35 min, until 10:05. After that, the wave amplitude drops rapidly and the wave is lost in the ambient noise. The wave is not easily visible in individual Dopplergrams. The wave front at 09:37 when the amplitude was maximum is indicated in Fig. 2b.

To construct seismograms of the solar flare, we have tracked the Dopplergrams of the 124×124-Mm region around the flare to remove the solar rotation, and then remapped the Doppler images into polar coordinates centered at the point of the initial velocity impulse. A difference filter was applied to remove background velocities. After that the data were Fourier-transformed with respect to the azimuthal angle and the Fourier coefficients were plotted as functions of the angular distance from the initial point and time. Figure 3a shows the first coefficient of the Fourier transform corresponding to the azimuthally averaged signal (azimuthal order $m = 0$). This circular wave displays a set of ridges with a positive slope, that begins about 18 Mm from the flare at 09:32, and reaches $\approx$ 50 Mm at 09:48. The velocity of the wave packet increased from $\approx$ 30 km s^{-1} to $\approx$ 100 km s^{-1} as the wave moved from from 20 Mm to 120 Mm from the epicenter. The maximum amplitude of this wave was approximately 50 m s^{-1}.

We have also analyzed the dipole ($m = 1$) and quadrupole components ($m = 2$) of the flare wave. While the dipole component of the flare wave does not have a significant signal, the quadrupole component shows ridges at distances from 15 to 40 Mm from the flare. By applying a 5-min wide Gaussian filter along the time-distance ridge, we have extracted the signal of the first three components of the wave. The combined signals of these components, multiplied by a factor 4, are shown in Fig. 4 at three instances separated by 10 min. The wave amplitude is not uniform: initially it was higher in the North-South direction than in the East-West direction, and it was changing at the later times. The deviation from the azimuthal symmetry could result from anisotropy of the momentum impulse that would be the case if the impact was not normal to the surface, and from scattering on large-scale inhomogeneities in the active region.

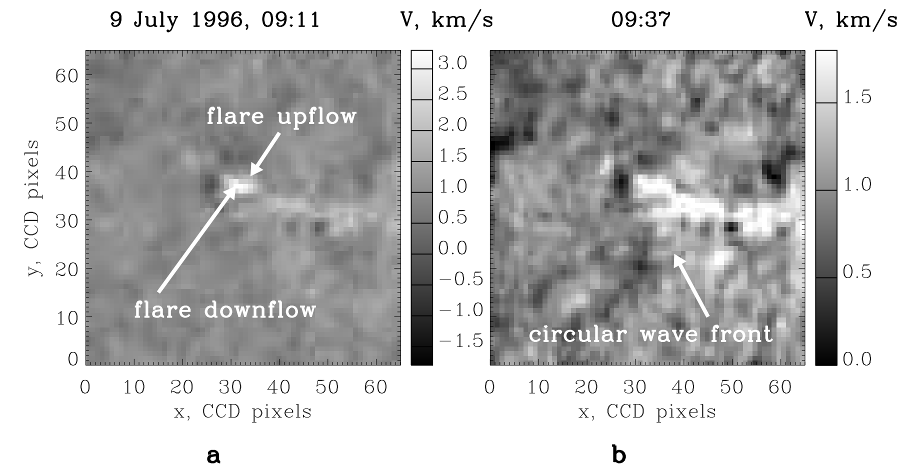

Figure 2: The MDI Dopplergrams of the flare region at 9:11 (a) and 9:37 (b). Bright areas correspond to downflows, and dark areas - to upflows.)

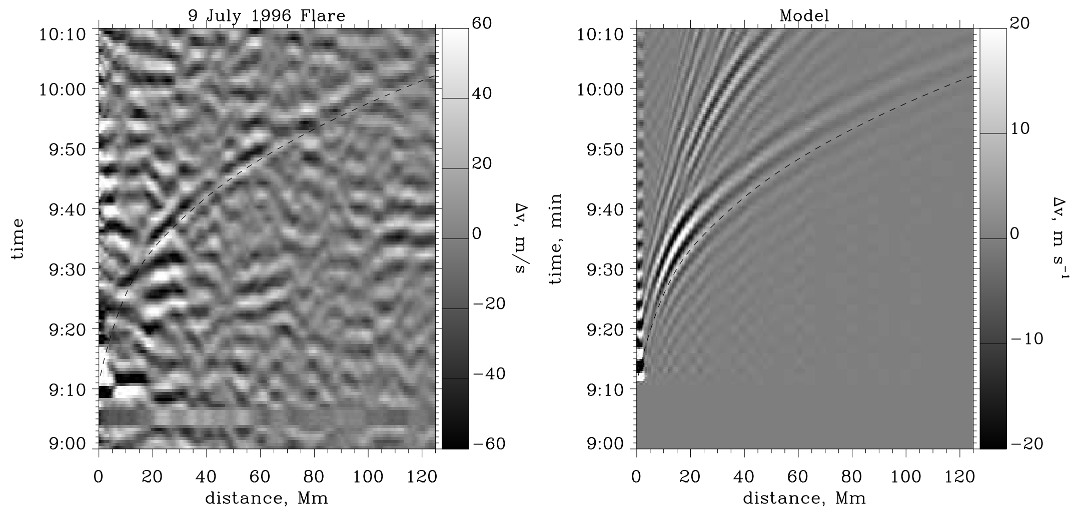

Figure 3: Time-distance diagrams representing the first azimuthal components of the observed (a) and theoretical (b) flare seismogram constructed from 1-min velocity differences. The theoretical flare seismogram computed for a localized momentum impulse of 10^{22} g cm s^{-1} applied to the solar surface at 09:11. The dashed curves in both panels show the theoretical time-distance relation for acoustic rays initiated at the flare core at 09:11.

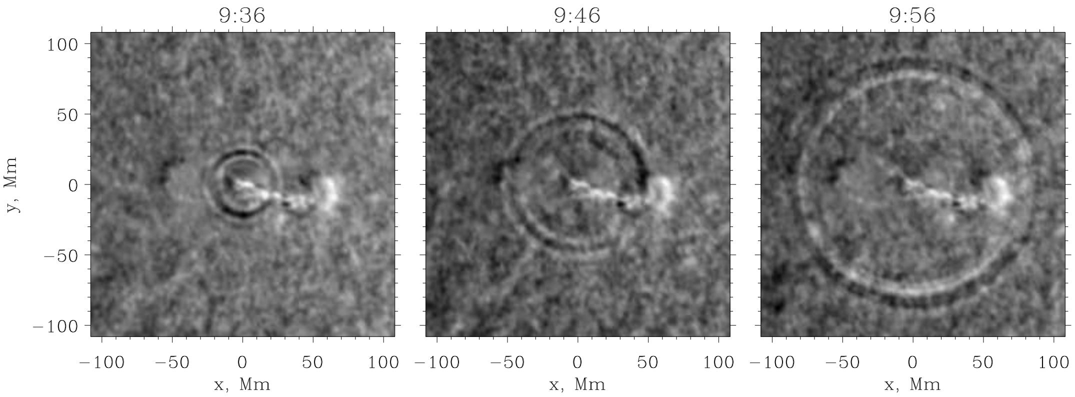

Figure 4: Remapped and filtered Dopplergrams at 9:36, 9:46, and 9:56, after 25, 35 and 45 min after the X-ray flare. The flare signal was extracted from the first three components ($m = 0, 1$ and 2) of the azimuthal Fourier transform by applying a 5-min wide Gaussian filter along the time-distance ridge of Fig. 2a. Then the signal combined from these three components was multiplied by a factor 4 to enhance it, and superimposed on the remapped Dopplergrams.

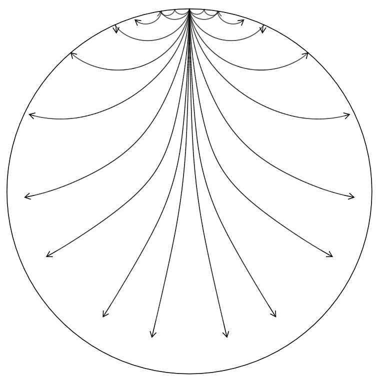

Figure 5: Samples of theoretical ray paths of the acoustic waves excited by flare and propagating through the solar interior 1h30m after the flare.

We have compared the observational results a theoretical models of the flare seismic response, which has predicted a similar kind of ripples.[9] The theoretical time-distance diagram for the 1-min velocity differences shown in Fig.3b reveals several sets of ridges. The lowest ridge corresponds to the waves appeared at a given distance on the surface after the first skip, the second ridge which is above of the first ridge corresponds to two skips, etc. The theoretical ray paths of acoustic waves from a flare source are illustrated in Figure 5. In the observed time-distance diagram (Fig. 3a), one can easily see only the first ridge. Also, the amplitude of the first ridge decays much faster in the model then it does in the observations. These discrepancies are not explained yet.

The maximum amplitude of the theoretical seismic wave matches the observation if the flare momentum transported to the photosphere in a downward propagating shock wave was about 3×10^{22} g cm s^{-1}. However, the momentum in the flare core, $\rho S v^2 \tau$, estimated from the MDI data (see Fig.1) for a density, $\rho \sim 10^{-8}$ g cm^{-3}, flare area, $S \sim 10^{17}$ cm^2, flow velocity, $v \sim 10^5$ cm s^{-1}, and impact duration, $\tau \sim 10^2$ s, is only $\sim 10^{21}$ g cm s^{-1}. This estimate is consistent with the momentum determined from previous H_α observations.[7] This suggests that additional sources of momentum and energy may have played a significant role in initiating the seismic wave during the impulsive phase of the flare. It is quite possible that the subsurface are heated strongly by the flare thermal wave propagating ahead of the shock[6] or directly by high-energy electrons and protons. If this the case then the seismic flare source may be located in subsurface layers causing a stronger impact on the Sun.

The seismic flare ridges in Fig. 3a are similar to the ridge pattern of the time-distance diagrams obtained by cross-correlating the oscillation signal between different regions on the solar surface.[10] However, to detect the time-distance ridges the cross-correlation function has to be averaged over several hours of data. Thus, flares provide a unique opportunity to do time-distance seismology of active regions based on localized impulsive sources.

The detection of the seismic response to a solar flare opens interesting perspectives for flare seismology and understanding the effects of flare processes in the Sun's interior.

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