X-Ray Flare Quakes the Sun

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Solar flares in which the Sun's magnetic energy is released in the form of X-ray radiation, particle beams and high-speed plasma flows are the strongest high-energy impulsive events affecting the Earth's space environment. Using data from the Solar and Heliospheric Observatory (SOHO), we discover that the flares also affect the Sun's interior, generating seismic waves similar to earthquakes. The seismic wave caused by a moderate X-ray flare on 9 July 1996 propagated to a distance of 120,000 km from the flare site with an averaged speed of about 50 km s^{-1} on the solar surface (photosphere) 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 internal structure of active regions.

The observed seismic response to the solar flare was stronger than the expectations based on the current understanding of the flares as giant electromagnetic explosions in the upper chromosphere and corona, several thousand kilometers above the photosphere level, and on previous attempts to detect the seismic response in ground-based data[1, 2]. The solar surface is covered by low-frequency (3 mHz) sound waves stochastically excited in millions of small convective elements - granules. These stochastic waves have been used in helioseismology to probe the large-scale structures of the Sun's interior[3]. The excitation of those waves (essentially by turbulent convection) is much different from the excitation of seismic disturbances on Earth. However, the excitation of disturbances by solar flares is quite similar to earthquakes in many respects, the most obvious being the impulsive localized release of energy and momentum.

The flare of 9 July was the only significant X-ray flare observed in 1996 because solar activity associated with sunspots and flares was near at the minimum of its 11-year cycle. This was a fairly moderate flare. When solar activity nears its maximum, observations of flares with several times this energy are not uncommon. More energetic flares are expected to shake the Sun more strongly.

The X-ray impulse of this flare (classified as X2.6/1B) was first detected by BATSE (Burst and Transient Source Experiment) on board the Compton Gamma Ray Observatory at 09:07:49 UT and reached a sharp maximum at 09:09:40 (Fig. 1). The magnetic field measurements from the Michelson Doppler Imager (MDI)[4] instrument on SOHO show that the flare 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. The MDI Dopplergrams reveal 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 on the Sun. The velocity impulse shown in Fig.1 was almost as sharp as the 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 'thick-target' model of solar flares[5, 6, 7, 8].

These models predict a strong downward propagating shock originating after a high-energy electron beam heats the cool chromospheric 'target'. The impact of this shock causes the seismic response.

By simply displaying the MDI Dopplergrams in sequence, we have detected flare ripples - circular wave packets propagating from the flare and resembling ripples from a pebble thrown into a pond. The seismic wave was first detected at about 09:30, approximately 20 min after the flare, at a distance of ≈ 18 Mm from the flare site. The wave was clearly observed in the sequence of Dopplergrams for about 35 min, until 10:05. After that, the amplitude dropped rapidly and the disturbance was lost in the ambient noise. The wave is not easily visible in individual Dopplergrams. Fig. 2b indicates the location of the wave front at 09:37 when the amplitude was greatest.

We have constructed seismograms of the solar flare by remapping the Doppler images into polar coordinates centered at the point of the initial velocity impulse, and then applying a Fourier transform with respect to the azimuthal angle. Figure 3 shows the first coefficient of the Fourier transform corresponding to the azimuthally averaged velocity perturbation, i.e. symmetrical circular waves, as functions of time and the distance from the initial point. In this seismogram the circular disturbance results in a set of ridges with a positive slope. The ridges began about 18 Mm from the flare at 09:32 and reached ≈ 120 Mm at 10:02. The velocity of the wave packet increased from ≈ 30 km s^{-1} to ≈ 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 compared the observational results with theoretical models of the flare seismic response that predict similar ripples[9]. The maximum theoretical amplitude matches the observation if the shock momentum transported to the photosphere in a downward propagating shock wave was about 3×10^{22} g cm s^{-1}. This is larger than the flare momentum typically estimated from spectral observations[7, 10]. We have also analyzed the dipole and quadrupole components 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, which presumably resulted from scattering on the magnetic structures of the active region.

The detection of the seismic response to a solar flare opens interesting prospects for flare seismology and for determining the effects of flare processes in the Sun's interior. Substantially stronger and larger X-ray flares are observed in other stars. Detection of 'starquakes' caused by those flares might be an interesting challenge for stellar astronomy.

References

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Figure 1: 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 with crosses).

Figure 2: The MDI Dopplergrams of the flare region showing the line-of-sight velocity: a) at 09:11, immediately after the X-ray pulse; and b) at 9:37, when the flare wave reached the maximum amplitude. Bright areas correspond to downflows, and dark areas - to upflows.

Figure 3: Flare seismogram representing the axisymmetrical components of the velocity disturbance. The dashed curve shows the theoretical time-distance relation for acoustic rays initiated at the flare core at 09:11. The flare signal is a black-and-white ridge around (mostly above) this curve. Other disturbances on the diagram are solar noise.