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SEISMIC RESPONSE TO SOLAR FLARES: THEORETICAL PREDICTIONS

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ABSTRACT

We present initial results of theoretical modeling of oscillations excited inside the Sun during the impulsive phase of a solar flare. During this phase a high-energy electron beam heats the upper layers of the chromosphere, resulting in explosive evaporation of chromospheric plasma at supersonic velocities. This upward motion is balanced by recoil of the lower part of the chromosphere downward into the Sun that excites propagating waves in the solar interior.

We demonstrate that for a typical impulsive energy-release event the momentum of the downflowing plasma is about 10^{22} g cm s^{-1} and the maximum amplitude of individual p modes will not exceed 1 mm s^{-1}. Therefore, a seismic response to only a very large flare with multiple energy sources can possibly be detected in oscillation power spectra. It may be possible to detect a different kind of seismic response due to a coherent signal of outgoing waves, the amplitude of which can reach 1 m s^{-1} for the typical event. We compare flare effects with a cometary impact on the Sun.

Keywords: *Sun's interior, oscillations, solar flares, comets, seismograms, SOHO*

1. INTRODUCTION

Solar flares and comets which collide with the Sun are the most strongly localized disturbances on the solar surface, that generate seismic waves propagating into the Sun. They may contribute to the excitation of the solar oscillations (Wolff, 1972, Isaak, 1981). Investigation of seismic response to solar flares is one of the primary objectives of the SOI. There are two principle effects to look for: 1) an increase of amplitudes of oscillation modes, and 2) waves travelling away from the flare.

There were at least two attempts to detect the response of the five-minute oscillations to solar flares. Haber et al (1988a, b) found a substantial increase in power of p modes of radial order 5 on the day after a major white-light flare. However, the power of the modes other than p_5 did not change significantly. They also found a substantial (19%) increase of power in outward travelling waves during the flare. In contrast, Braun and Duvall (1990) who observed another flare concluded that the power increase was below 10%.

It is difficult to predict theoretically the seismic effects of solar flares because their physics and, in particular, processes in the lower chromosphere and the photosphere are poorly understood. For instance, it is likely that restructuring of the magnetic field in the flare region results in a pressure perturbation comparable or even stronger than that produced by energy-release events in the higher atmosphere, considered in this paper.

We present initial results of theoretical modeling of oscillations excited inside the Sun during the impulsive phase of a solar flare. The cometary impact is similar to the flare effect. They both can be described in terms of the total momentum transferred to the oscillation modes.

2. MODEL OF IMPULSIVE PHASE OF SOLAR FLARES

We have used a numerical gas-dynamic model of the chromospheric heating produced by a nonthermal electron beam (Kostyuk & Pikelner, 1974; Zharkova & Brown, 1994) to estimate the total momentum of the flow moving downward to the photosphere. During this phase a high-energy electron beam heats the upper layers of the chromosphere, resulting in explosive evaporation of chromospheric plasma at supersonic velocities. This upward motion is balanced by recoil of the lower part of the chromosphere downward into the Sun that excites propagating waves in the solar interior.

The results of our computations are shown in Fig. 1. The downward flow consists of a radiative shock wave moving with velocity 10–20 km/s in the lower chromosphere. The plasma density behind the front is about 100 times higher than in the surrounding unperturbed chromosphere (Livshits *et al.*, 1981). The region of the compressed plasma behind by the shock front sometimes is identified as ‘chromospheric condensation’; it is probably the main source of red-shifted H_α emission of the flares.

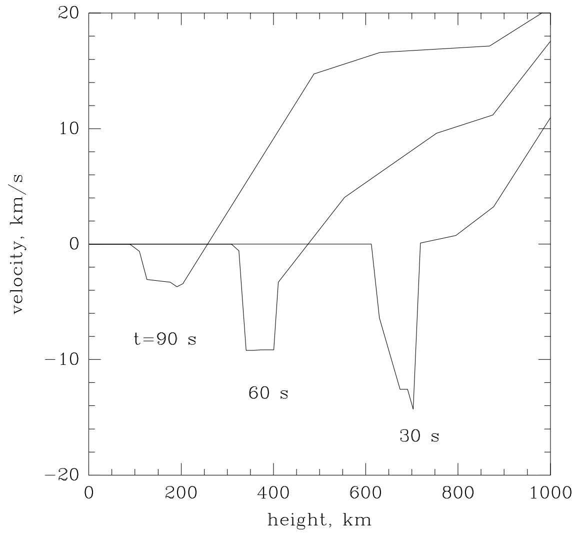

Figure 1: *Velocity in the lower chromosphere during the impulsive phase of a solar flare. Electron flux density: 10^{12} erg/cm^2/s, spectral index: 3.*

The total momentum estimated from this model, assuming the flare area 10^{19} cm^2, is 10^{21} g cm/s. Using X-ray and H_α data, Zarro *et al.* (1988) estimated the total momentum of the downflowing plasma to be 7×10^{21} g cm/s. We adopt the total momentum 10^{22} g cm/s in the estimate of the seismic effects.

3. SEISMIC CONSEQUENCES OF FLARES

We have applied a normal-mode approach by Dziewonski & Gilbert (1983) to compute the seismic response. All the solar modes with frequencies below the acoustic cutoff frequency and of angular degree up to 1000 were included in the computations. The effect of the high-frequency modes was taken into account using an asymptotic theory.

Figures 2–6 show evolution of the perturbation on the solar surface, produced by a flare impact with the total momentum 10^{22} g cm/s.

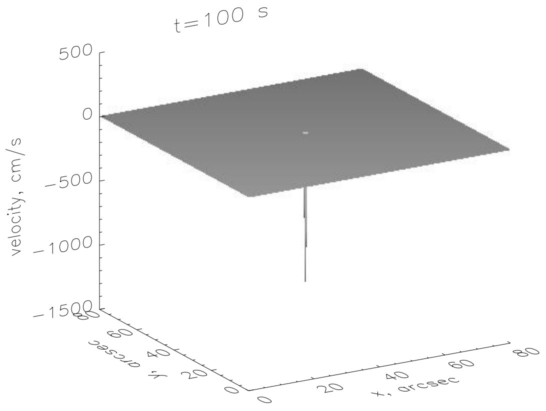

Figure 2: *Velocity perturbation in the outgoing wave 100 s after the flare shock reached the photosphere. The flare was located at $x = y = 40$ acrsec.*

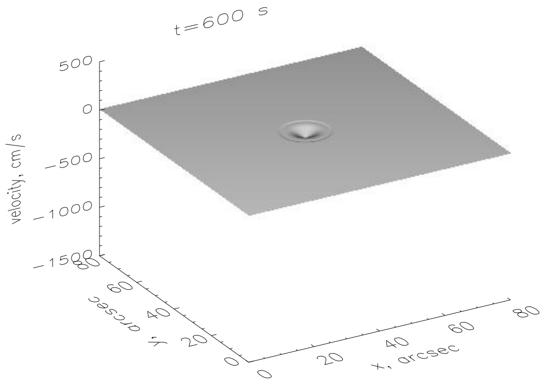

Figure 3: *The same as in Fig. 2 but after 600 s.*

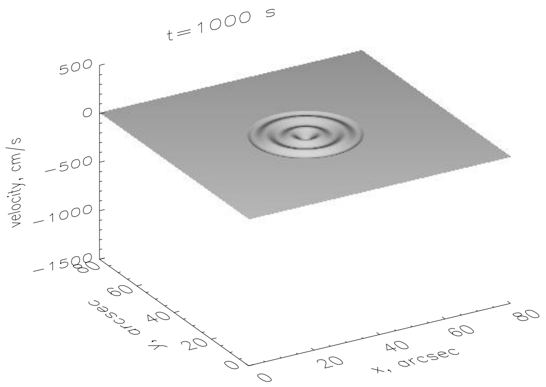

Figure 4: *The same as in Fig. 2 but after 1000 s.*

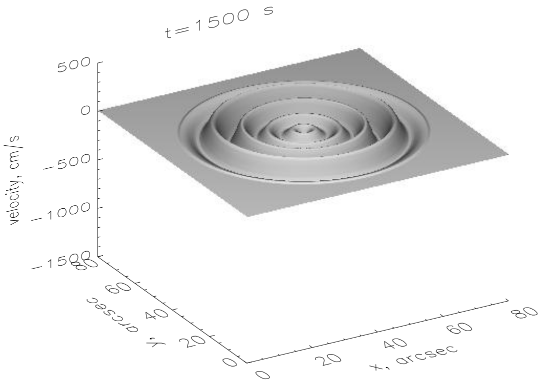

Figure 5: *The same as in Fig. 2 but after 1500 s.*

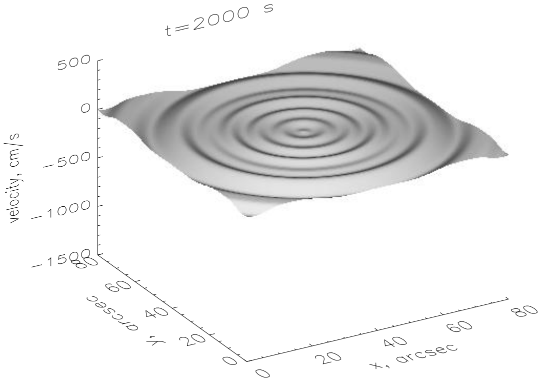

Figure 6: *The same as in Fig. 2 but after 2000 s.*

The amplitude of the circular wave propagating from the flare source does not exceed a few meters per second. This outgoing wave represents a coherent signal of superposition of several thousand normal modes. However, the amplitudes of individual modes are less than 1 mm/s (Figs 7 and 8). Since amplitudes of the observed modes are at least 10 times larger, the result of the flare impact is difficult to detect in the oscillation power spectra (Haber *et al.*, 1988a, b). It is interesting that the p_5 modes dominate at $l = 150 - 200$. In the corresponding part of the $k - \omega$ diagramm, the oscillation power in the p_5-ridge can be 20% larger than in the other ridges. However, in our model the effect is not as strong as it was observed by Haber *et al.* (1988a).

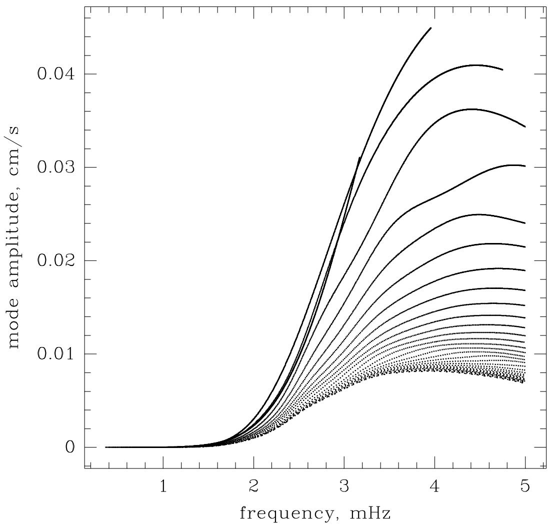

Figure 7: *The amplitudes of individual modes of oscillations plotted versus the mode frequencies. The modes of the similar radial order are grouped in ridges. The total momentum of the flare impulse is* 10^{22} *g cm/s.*

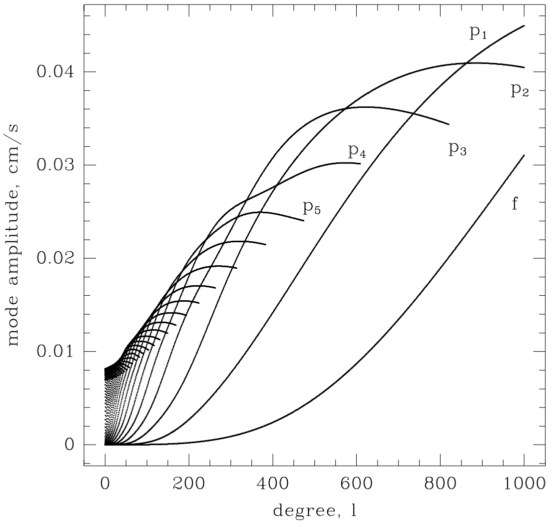

Figure 8: *The same as in Fig. 7 but versus the angular degree l.*

It might be more prospective to look for a coherent signal of the outgoing waves. Figure 9 shows the velocity as a function of time at different angular distances from a flare source. The velocity may be few meters per second near the flare, but it rapidly decreases as the distance increases. The amplitude increases again at the antipodal point ($\theta = \pi$), where the waves converge, reaching the maximum amplitude 7 hours after the flare.

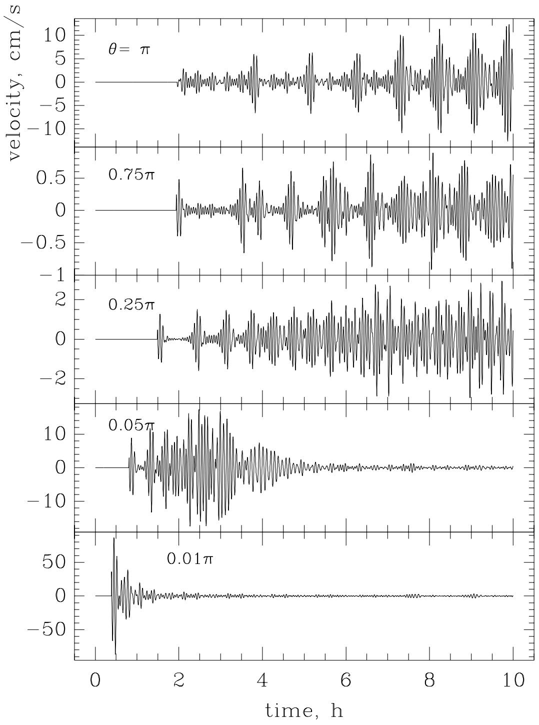

Figure 9: *Flare seismograms: velocity at different angular distances θ from a flare source with total momentum 10^{22} g cm/s*

4. DISCUSSION

We demonstrate that for a typical impulsive energy-release event the momentum of the downflowing plasma is about 10^{21-22} g cm s^{-1} and the maximum amplitude of individual p modes will not exceed 1 mm s^{-1}. Therefore, a seismic response to only a very large flare with multiple energy sources can possibly be detected in oscillation power spectra. It may be possible to detect a different kind of seismic response due to a coherent signal of outgoing waves, the amplitude of which can reach 1 m s^{-1} for the typical event. Observations of seismic response to solar flares will provide important information about the flare mechanism and the subphotospheric structure of active regions.

A comet with the mass 10^{17} g, which is about the mass of Comet Halley, carries the momentum 7×10^{23} g cm/s. Therefore, the cometary impact is 70 times stronger than the flare one. It should be observable in the power spectrum of high-degree modes, amplitudes of which can reach 2 cm/s. However, the amplitudes of low-degree modes which are observed in whole-disk measurements (Isaak et al., 1984) will be only 0.5 cm/s higher after the impact. The seismic response from a comet should be also seen as the outgoing wave. Our results contradict the estimates by Gough (1994) who concluded that a comet should be 6 times more massive to produce an observable seismic response.

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