ON THE ORIGIN OF THREE SEISMIC SOURCES IN THE PROTON-RICH FLARE OF 2003 OCTOBER 28

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ABSTRACT

The three seismic sources, S1, S2, and S3, detected from MDI Dopplergrams using the time-distance (TD) diagram technique are presented with the locations, areas, and vertical and horizontal velocities of the visible wave displacements. Within the data cube of 120 Mm, the horizontal velocities and the wave propagation times vary slightly from source to source. The momenta and start times measured from the TD diagrams in sources S1–S3 are compared with those delivered to the photosphere by different kinds of high-energy particles with the parameters deduced from hard X-ray and γ-ray emission, as well as by the hydrodynamic shocks caused by these particles. The energetic protons (power laws combined with quasi-thermal ones, or jets) are shown to deliver momentum high enough and to form the hydrodynamic shocks deep enough in a flaring atmosphere to allow them to be delivered to the photosphere through much shorter distances and times. Then the seismic waves observed in the sources S2 and S3 can be explained by the momenta produced by hydrodynamic shocks, which are caused by mixed proton beams and jets occurring nearly simultaneously with the third burst of hard X-ray and γ-ray emission in the loops with footpoints in the locations of these sources. The seismic wave in source S1, delayed by 4 and 2 minutes from the first and second hard X-ray bursts, respectively, is likely to be associated with a hydrodynamic shock occurring in this loop from precipitation of a very powerful and hard electron beam with higher energy cutoff mixed with quasi-thermal protons generated by either of these two bursts.

Subject headings: hydrodynamics — Sun: flares — Sun: helioseismology — Sun: X-rays, gamma rays

Online material: color figures

1. INTRODUCTION

The first successful attempt to observe seismic waves in SOHO MDI Dopplergrams in the form of ripples centered on the X2.6/1B solar flare of 1996 July 9 was reported by Kosovichev & Zharkova (1998). The authors presented a helioseismic response (solar quake) propagating on the solar surface from the flare location, with a strong localized plasma downflow of about 1.5 km s\(^{-1}\) at the location of the H\(\alpha\) flare impulse occurring within a minute of the hard X-ray maximum (Kosovichev & Zharkova 1998).

A comparison of the observations with the theoretical model (Kosovichev & Zharkova 1995) revealed that the momentum required to produce the observed seismic response (\(\sim 2 \times 10^{22} \text{ g cm s}^{-1}\)) is 1 order of magnitude higher than those of \(\sim 10^{21} \text{ g cm s}^{-1}\) observed from the plasma downflows in the MDI Dopplergrams (Kosovichev & Zharkova 1998). The required momentum could be delivered by a hydrodynamic shock appearing at the injection of a very hard (\(\gamma = 3\)) and intense (\(F_0 = 10^{12} \text{ erg cm}^{-2} \text{ s}^{-1}\)) electron beam. These parameters were arbitrarily selected, since there are no detailed hard X-ray observations available for this flare.

However, the travel time of this shock to the photosphere is more than 2 minutes, while the time at which the helioseismic response started in TD diagrams coincides very closely with the time of the hard X-ray impulse and does not reveal the 2 minute delay. Hence, there should be some additional sources that can deliver the required momentum to the solar photosphere within a very short timescale, coinciding with the start time of a hard X-ray impulse.

Recent observations, which reported helioseismic emission from the solar flares of 2003 October 28 and 29 using the helioseismic holography technique (Donea & Lindsey 2005; DL05 hereafter), revealed another five sources that occurred in the active region NOAA 10486 with seismic emission at frequencies from 3 to 7 mHz, four of them in the flare that occurred 2003 October 28 (DL05). The flare hard X-ray emission at the very start, 11:01:00 UT, was observed by KORONAS (Kuznetsov et al. 2006) and INTEGRAL (Gross et al. 2004; Kiener et al. 2006), while RHESSI started observations only at 11:06:00 UT (Hurford et al. 2006). However, two of the four sources for this flare reported by DL05 were well aligned with the hard X-ray and γ-ray signatures observed by RHESSI after 11:06:00 UT (Hurford et al. 2006).

Hence, in order to establish a connection between high-energy particles and the seismic source agents, let us investigate in more detail the velocities of vertical and horizontal displacements, or the ridges, associated with these seismic waves in the 2003 October 28 flare by applying the time-distance diagram technique (TD method, hereafter; Kosovichev & Zharkova 1998) to the MDI Dopplergrams and by deducing the momenta required to cause the observed ridges. Then we can compare them with those delivered by high-energy particles of different kinds via low-temperature hydrodynamic shocks occurring in the chromosphere in response to the particle injections and traveling toward the photosphere.

The observations used in this study are presented in § 2; active region morphology is described in § 2.1, the available high-energy observations in § 2.2, the TD diagrams technique in § 2.3, and the observed ridges of the seismic sources detected in § 2.4. A theoretical basis for the energy transport from the corona to the lower atmosphere is described in § 3, including the heating functions of different particles in § 3.1 and a hydrodynamic response to the injection of particle beams or jets in § 3.2. The evaluation of the wave parameters in the helioseismic sources and their comparison with the momenta delivered by hydrodynamic shocks for
different kinds of particles is discussed in § 4. Conclusions are drawn in § 5.

2. DESCRIPTION OF THE OBSERVATIONS

2.1. Active Region Morphology and Magnetic Field

The X17.2 flare occurred on 2003 October 28 in the very active region NOAA 10486 at the location E18°S20°. GOES observation starts at 9:41 UT, lasting until 11:24 UT with the maximum at 11:10 UT in soft X-rays, and lasting until 18:00 UT in Hα emission. The active region NOAA 10486 had a complex delta sunspot and produced dramatic flare activities in the descending phase of solar cycle 23 with three X-class flares, i.e., an X17 flare on 2003 October 28, an X10 flare on 2003 October 29, and an X8.3 flare on 2003 November 2, as well as many weaker ones (Xu et al. 2005).

By tracing the changes of the sunspot group simultaneously with the TRACE white-light images, the penumbral segments are found to decay rapidly and permanently right after each of three X-class solar flares occurred in this region, with the neighboring umbral cores becoming darker (Liu et al. 2004). It was concluded that these variations reflect the changes of the photospheric magnetic fields associated with the decaying penumbral areas, with some parts of them being converted into the umbral field. This implies the emergence of a new magnetic flux along the magnetic neutral line and that a strong magnetic shear developed in this active region, which plays an important role as the trigger of the X-class flare on October 28 (Xu et al. 2005). By tracing the changes of the sunspot group simultaneously with the TRACE white-light images, the penumbral segments are found to decay rapidly and permanently right after each of three X-class solar flares occurred in this region, with the neighboring umbral cores becoming darker (Liu et al. 2004). It was concluded that these variations reflect the changes of the photospheric magnetic fields associated with the decaying penumbral areas, with some parts of them being converted into the umbral field. This implies the emergence of a new magnetic flux along the magnetic neutral line and that a strong magnetic shear developed in this active region, which plays an important role as the trigger of the X-class flare on October 28 (Xu et al. 2005).

In the present paper we use the MDI Dopplergrams obtained aboard SOHO from 11:00 UT until 13:00 UT with 1 minute cadence, supported by the MDI magnetograms and white-light images taken from the Solar Feature Catalogues (SFCs) at the times closest to the flare setup time (Zharkova et al. 2005). In Figure 1 all the sunspots detected in the MDI white-light image at 11:05:33 UT with the automated technique (Zharkov et al. 2005) taken from SFCs are depicted with their umbras and pores. In Figure 2 the sunspot locations are overplotted onto a magnetogram (top) and Dopplergram (bottom) taken at the time 11:05:33 UT. It appeared that three out of the four seismic sources X1–X4 reported by DL05 occurred either around the new umbras appearing next to the old ones (X1, X3) or in a new magnetic flux of the opposite polarity appearing in the existing umbra (X4; see Fig. 2).

2.2. Hard X-Ray, γ-Ray Emission and Accelerated Particles

The flare on 2003 October 28 started in high-energy emission before 11:00 UT that was only observed by KORONAS (Kuznetsov et al. 2006) and INTEGRAL (Gross et al. 2004; Kiener et al. 2006), while the RHESSI payload did not start observing until 11:06:00 UT (Hurford et al. 2006). There is also a very strong coronal mass ejection, an interplanetary shock wave with an onset time of 11:01:39 UT, and high-energy particles registered at the Earth orbit (Kuznetsov et al. 2006; Miroshnichenko et al. 2005).

The flare light curves in γ-rays measured by the SONG (Solar Neutrons and Gamma rays) instrument aboard KORONAS are

Fig. 1.—Sunspot group located in the active region NOAA 10486 with the large trailing and two smaller leading sunspots obtained in the white-light image at 11:05:11 UT from the Solar Feature Catalogue.

Fig. 2.—Same sunspot group as in Fig. 1 plotted onto the MDI magnetogram 11:11:33 UT (top) and on the Dopplergram (bottom) with the locations of the seismic sources marked by X1–X4 (last four rows in Table 1) detected by the holographic method (Donea & Lindsey 2005) with the γ-ray sources observed by RHESSI, marked as G1 and G2 (Hurford et al. 2006).
plotted in Figure 3 (two left columns) with the particle energy spectra in Figure 3 (two right columns; a courtesy of V. Kurt and the KORONAS team; Kuznetsov et al. 2006). Similar light curves were observed in the \( \gamma \)-continuum (2.8–3.7 and 7.6–10 MeV) and \( \gamma \)-lines (2.22, 4.44, and 6.13 MeV) by the instruments aboard INTEGRAL (Fig. 5 in Gross et al. 2004).

These light curves revealed the three distinct phases in the flare evolution: a short impulsive phase A (under 1 minute) with a sharp increase of the continuum emission in both channels with the photons detected up to 15 MeV, the SPI energy limit; and two longer increase of the continuum emission in both channels with the photon energy spectra (phase B) and a much smoother increase of the line emission in all three lines (phase C).

The start time of the flare impulsive phase was about 11:01:00–11:02:00 UT (see Fig. 3), based on measurements by INTEGRAL (Gross et al. 2004) and KORONAS (Kuznetsov et al. 2006). From 11:01:39 UT until 11:05:40 UT the brightest outburst in energy was in the range of 0.5–40 MeV, while the protons >100 MeV were only detected at about 11:06:00 UT when RHESSI also started to observe. The KORONAS light curves show two rather prominent peaks in \( \gamma \)-ray emission at 11:02:00 and 11:03:00 UT in the range from 0.5 to 41 MeV (corresponding to phase A and the start of B in the INTEGRAL) and another two peaks appearing later, at about 11:06:00 UT in the lower energy ranges of 0.15–4 and 26–100 MeV, corresponding to phase B from INTEGRAL.

In the first phase, the two \( \gamma \)-continuum peaks are concluded to be produced mainly by a bremsstrahlung spectrum generated by electrons with energies up to 150 MeV, with a small \( \gamma \)-ray increase in the range of 1.5–7 MeV (Gross et al. 2004; Kuznetsov et al. 2006). In this phase, the \( \gamma \)-line emission was also observed by KORONAS, which indicates a presence of protons with energies >30 MeV, but not higher than 200 MeV, because of the absence of photons from the \( \pi \)-decay process. The photon energy spectra obtained during the first phase (see Fig. 3, two right columns) are single power laws with spectral indices of about 2 at the lower energy part (<70 keV) and 3.5–4 at higher energies (Kuznetsov et al. 2006; Kurt 2006, private communication).

The second phase, a delayed one where the other two peaks are observed in \( \gamma \)-rays by KORONAS, INTEGRAL, and RHESSI, has very noticeable plateaus in the energy spectra in the range of 25–100 MeV (see the middle and bottom rows in Fig. 3, two right columns), first appearing at about 11:06:10 UT. In addition, there are higher energy protons >200 MeV appearing after 11:06:00 UT, indicated by a presence of \( \pi \)-decay photons (Kuznetsov et al. 2006; Share et al. 2004).

The images of the sources of hard X-ray (200–300 keV) and \( \gamma \)-ray emission (2.2 MeV) obtained by RHESSI (Hurford et al. 2006) are marked as G1 and G2 on the active region image in Figure 2. The images reveal that, at least after 11:06:00 UT when RHESSI started to observe, there were two footpoints with the hard X-ray and \( \gamma \)-ray sources, which have slightly different spatial locations with the seismic sources located between them.

The spectral indices of the proton energy spectra deduced from the ratios of \(^{12}\)C and \(^{16}\)O lines observed in phase B, or after 11:06:00 UT, from INTEGRAL vary from 3 to 3.8 (Kiener et al. 2006). This is close to those of 2.8 ± 0.4 also reported after 11:06:00 UT by the RHESSI measurements from the de-excitation line 2.22 MeV and positron annihilation line 511 keV with a total number of protons of about \( 10^{33} \) (Share et al. 2004).

Hence, in this flare there are ample indications from the observations of high-energy emission about a few events with particles arriving at various times, from 11:02:00 until 11:07:00 UT at the footpoints.

2.3. The Time-Distance Diagrams Technique

Now let us investigate from MDI Dopplergrams (Scherrer et al. 1995) this flare evolution at the photospheric level and below. We use 1 minute cadence Dopplergrams for the hour starting at 11:00:00 UT. Since the typical oscillation frequencies associated with quakes (Kosovichev & Zharkova 1998; Donea & Lindsey 2005) are higher than the background oscillations (3 mHz), we also apply frequency filtering centered at 5–6 mHz in order to increase the signal-to-noise ratio.

The obtained velocity distributions in the area with radius of 120 Mm are fit by a circular wave using the angular Fourier
transform for the angle $\theta$ that can be described by the angular Fourier transform (J. Christensen-Dalsgaard 2003, Lecture Notes on Solar and Stellar Helioseismology) for the angle $\theta$ as follows:

$$v(r, \theta, t) = \sum_{m=0}^{2} v_{m}^{0}(r, t) e^{im\theta},$$

where $m = 0$ denotes a circular wave, $m = 1$ a dipolar wave, and $m = 2$ a quadruple wave. Practically, as the previous observation has shown (Kosovichev & Zharkova 1998), we do not expect to observe waves higher than these three types, because of observational noise. In the present study we extract only a circular wave, while the dipolar wave was also registered for this flare by Kosovichev (2006).

The MDI Dopplergrams are remapped into polar coordinates with the centers around the location of the holographic seismic sources X1–X4 (Donea & Lindsey 2005). The new velocity distributions $v(r, \theta, t)$ are obtained as the function of time $t$ and their distance $r$ from the center (defined with the accuracy of a single pixel).

Then we extract the velocities $v_{m}^{0}(r, t)$ for every $r$, averaged over various angles $\theta$ for $m = 1$ in the data cube of 120 Mm, and measure the horizontal displacements of the propagating seismic waves for the different times (J. Christensen-Dalsgaard 2003, see footnote 3), i.e., $v_{0}^{0}(r_{1}, t_{1})$, $v_{1}^{0}(r_{2}, t_{2})$, that can be plotted for different times ($\gamma$-axis) and distances ($x$-axis) as a TD diagram (Kosovichev & Zharkova 1998).

### 2.4. The Observed Seismic Sources

In order to precisely detect the seismic wave centers, we selected the areas of $20 \times 20$ pixels around the locations provided by DL05 (Table 1, last three columns). Then for the four sources (X1–X4) from Table 1 we obtained 400 TD diagrams (for each source), which were visually investigated for the pixel locations with detectable ridges denoting the seismic wave propagation. Then the pixels with the detectable ridges were used to define the total areas for each quake, and their centers of gravity were used as the centers of the seismic waves.

For the detection of seismic sources we use the 1 minute cadence Dopplergrams from 11:00:00 until 13:00:00 UT. In general, in all the MDI Dopplergrams we have detected 11 locations with downward motion larger than 1 km s$^{-1}$ (Fig. 4), using the automated technique (Zharkov et al. 2005), while only three of them, S1, S2, and S3, have revealed detectable ridges, or quakes (Fig. 6). For each seismic source we extracted the data cube of $120 \times 120$ Mm centered in the center of gravity of the downward Doppler motions in this source, remapped them into the polar coordinates, and applied the Fourier technique (eq. [1]) for a distance from the center where the initial impulse is applied (the center of gravity) of up to 120 Mm. The deduced locations for seismic sources S1, S2, and S3 with detectable ridges are summarized in Table 1 (first three rows) and compared with sources X1–X4 detected by DL05 (last four rows).

### TABLE 1

| Source       | $L_{0}$ (deg) | $B_{0}$ (deg) |
|--------------|---------------|---------------|
| **Our sources**          |               |               |
| S1           | 287.28        | -15.96        |
| S2           | 284.72        | -17.62        |
| S3           | 291.00        | -16.64        |
| **DL05**     |               |               |
| X3           | 287.05        | -15.78        |
| X1           | 285.45        | -17.61        |
| X4           | 291.46        | -16.43        |
| X2           | 285.86        | -16.01        |

**Note.**—The heliographic locations $L_{0}$ and $B_{0}$ of the three seismic sources detected by the TD technique (first three rows) and four seismic sources in the flare 2003 October 28 reported from the holographic method (Donea & Lindsey 2005; last four rows).
exceed 1.5–2.0 minutes, starting at or after 11:05:00 UT with the maximum a minute later and then decreasing for another 30–60 s back to the preflare magnitude.

The TD diagrams for our sources S1–S3 are presented in Figure 6 without and with the theoretical ray paths (white solid lines) for the source S1 (top), S2 (middle), and S3 (bottom). The start times of the seismic waves are slightly different in each source, varying from about 11:05:00 to 11:06:00 UT for source S1 to 11:06:00 UT for sources S2 and S3. These times are more than 3 minutes later than the first maximum of hard X-rays for the source S1, but close to the second maximum in both hard X-rays and \( \gamma \)-rays, pointing to the presence of high-energy protons (>200 MeV) for sources S2 and S3 (Kuznetsov et al. 2006; Share et al. 2004).

At the very start of the seismic response, or ridge, source S1 (Fig. 6, top), corresponding to source X3 (DL05), reveals the initial horizontal velocity of about 42 km s\(^{-1}\) that increased in 50 minutes up to 140 km s\(^{-1}\) at distance of 120 Mm. The ridge in source S2 (middle), or source X1 in DL05, was slightly steeper compared to source S1, i.e., the seismic wave was slower; its velocity varies from 38 to 128 km s\(^{-1}\) in 53 minutes. The ridge in source S3 (Fig. 6, bottom), source X4 in DL05, shows the lowest velocity variations from 34 to 114 km s\(^{-1}\) in 60 minutes. Hence, the initial velocity in source S1 is higher and the seismic wave propagates toward the 120 Mm edge of the data cube slightly faster than in the other two sources, S2 and S3.

The areas of the seismic sources, defined by a presence of downward motions and detectable ridges, were about \( 5.05 \times 10^{17} \) cm\(^2\) for source S1, \( 3.34 \times 10^{17} \) cm\(^2\) for source S2, and \( 3.22 \times 10^{17} \) cm\(^2\) for source S3. Then, by using the downward velocities above (see Table 2) and comparing with the theoretical seismic ridges (Kosovichev & Zharkova, 1995, 1998), one can deduce the momenta required to cause the observed ridges: \( 4.0 \times 10^{22} \) g cm s\(^{-1}\) (S1), \( 3.7 \times 10^{22} \) g cm s\(^{-1}\) (S2), and \( 3.1 \times 10^{22} \) g cm s\(^{-1}\) (S3).

The locations of the seismic sources S1, S2, and S3 found from the TD diagrams are slightly different from those reported from the holographic method DL05; this could be a result of the different sensitivities of the techniques applied by us and DL05. The TD technique does not produce distinguishable ridges for source X2, which was seen after 11:07:00 UT (DL05). There was a weak downward source in the location of source X2 observed by MDI between 11:02:00 and 11:03:00 UT (the first maximum in hard X-rays), as was spotted in Figure 5 of DL05. While the locations of sources S1–S3 coincide with the dark spots inside the sunspot umbras, there is no indication of any new umbras in the location of source X2.

The absence of the fourth source in the TD diagrams could have a number of explanations. The source X2 could be rather weak, and thus not detectable by the TD technique, while it was seen by the holographic method. Other options are either that this source is an interference of the seismic waves produced by the two sources (possibly S1 and S2) or that it is located so close to source S1 that it
Fig. 6.—Frequency-filtered time-distance diagrams for the seismic sources: S1 without a ray path (top left) and S1 with the ray path (top right); similar for the sources S2 (middle) and S3 (bottom).
we merged them into the extended S1 source. However, the problem with the latter is that the TD diagram for S1 shows its start time at 11:05:00 UT. These are very puzzling questions that we, with the authors of the holographic method (DL05), are planning to investigate in the future for this and other flares.

3. THE PARTICLE ENERGY TRANSPORT

In order to evaluate the transfer into the ambient plasma of the particle momenta and energy after their injection from the top into a flaring atmosphere, let us investigate their heating functions and resulting hydrodynamic responses.

Let us assume that the protons or electrons accelerated in a reconnecting current sheet (RCS) with a strong longitudinal magnetic field occurred during this flare; then they can be ejected as power-law beams and completely or partially separated into opposite footpoints of the same loop (Zharkova & Gordovskyy 2004, 2005a). In addition to the electron or proton beams, let us consider the particles with Maxwellian (thermal) energy distributions shifted to higher energies accelerated along the separatrices of the RCS (Gordovskyy et al. 2005).

Therefore, we consider the four kinds of high-energy particles whose energy losses are converted into the ambient plasma heating: fast electron beams and fast proton beams with power-law energy distributions, and slow electrons and protons of the separatrices jets with thermal energy distributions.

3.1. The Heating Functions by High-Energy Particles

The energy deposition functions, or heating rates, for these particles are calculated using distribution functions found from the full kinetic approach by solving the Fokker-Planck equation for electrons losing their energy in collisions and Ohmic heating (Zharkova & Gordovskyy 2005b) and protons in the generation of kinetic Alfvén waves (KAWs) and their dissipation via Cherenkov resonance (Gordovskyy 2005; Gordovskyy et al. 2005).

The volume heating rates by all kinds of high-energy particles simultaneously present in the flaring atmosphere are calculated from the particle distribution functions as a vertical gradient of the beam energy flux:

$$ S(\xi) = -n(\xi) \frac{d[F_e(\xi) + F_p(\xi) + F_t(\xi)]}{d\xi}, $$

where $\xi = \int_{z_{\text{min}}}^{z_{\text{max}}} n(z)dz$ is a column density, i.e., a number of the ambient particles in the area of 1 cm$^2$ on a line of sight from the height $z_{\text{min}}$ to $z_{\text{max}}$, $n(\xi)$ is a total density of the ambient plasma at a given height, $F_e(\xi)$, $F_p(\xi)$, and $F_t(\xi)$ are the energy fluxes carried by fast electrons, “fast” protons, and “slow” protons (of separatrices jets), respectively. We do not include the energy losses by slow electrons, since these are negligible compared to the other particles (Gordovskyy et al. 2005). The heating rate per particle of the ambient plasma $P(\xi)$ is related to the volume heating rate $S(\xi)$ as $P(\xi) = S(\xi)/n(\xi)$. The variations of the density are considered from a hydrodynamic response below.

3.2. Hydrodynamic Response to the Particle Injection

Let us now consider a hydrodynamic response of the one-dimensional solar atmosphere to the injection of electrons and/or protons by taking into account the continuity, momentum, and energy equations for the ambient electrons and protons/ions.

The physical conditions in a flaring atmosphere can be described by a plasma density $n$, electron $T_e$, and ion $T_i$ temperatures, and a vertical velocity $v$. All these parameters vary with a vertical coordinate $z$, or a column density $\xi$, and time $t$. The ambient plasma response to the injection of high-energy particles is described by the hydrodynamic equations (see, e.g., Somov et al. 1981; Fisher et al. 1985a, 1985b, 1985c):

Continuity equation:

$$ \frac{\partial n}{\partial t} + n \frac{\partial}{\partial z} \left( \frac{v}{\mu k_B} \right) = 0. $$

Momentum equation:

$$ \frac{\partial v}{\partial t} + \frac{1}{\mu k_B} \left[ nk_B(T_e + x T_i) \right] = 4 \frac{1}{3} \frac{\partial}{\partial z} \left( \eta n \frac{\partial v}{\partial z} \right) + g(z). $$

Energy equation for ions:

$$ \frac{n k_B}{\gamma - 1} \frac{\partial T_i}{\partial t} - k_B T_i \frac{\partial n}{\partial t} + \frac{4}{3} \frac{\partial}{\partial z} \left( \eta n \frac{\partial T_i}{\partial z} \right) = Q(n, T_e, T_i). $$

Energy equation for electrons:

$$ \frac{n k_B}{\gamma - 1} \frac{\partial (x T_e)}{\partial t} - x k_B T_e \frac{\partial n}{\partial t} + n \chi \frac{\partial x}{\partial t} = n \frac{\partial}{\partial z} \left( \kappa n \frac{\partial T_e}{\partial z} \right) + P(n, T_e, T_i) - L(n, T_e, T_i). $$

Here $T_i$ and $T_e$ are the ion and electron temperatures, respectively, $n$ is the ambient plasma density, $x$ is the ionization degree of the ambient plasma, $\gamma$ is the adiabatic constant, $k_B$ is the Boltzmann constant, $\kappa$ is the thermal conductivity, $\eta$ is the ion viscosity, $\chi$ is the full ionization energy of a hydrogen atom, $\mu = 1.44 m_n$, and $g(z)$ is the acceleration due to gravity of the Sun. $P(n, T_e, T_i)$ indicates the volume heating rates provided by electrons owing to collisions, by electrons owing to Ohmic losses, by protons owing to collisions, and by KAWs; $L_{\text{rad}}$ is the volume radiative energy loss rate; and finally $Q(n, T_e, T_i)$ is the rate of energy exchange between ions and electrons.

The solution is sought in a limited region of the solar atmosphere $z_{\text{min}} \leq z \leq z_{\text{max}}$, with the minimum boundary located at $z_{\text{min}} = 2 \times 10^{17}$ cm$^{-2}$ and the maximum boundary, located deep in the photosphere at $z_{\text{max}} = 2 \times 10^{24}$ cm$^{-2}$. The initial atmosphere is assumed to be in hydrostatic equilibrium, i.e., $v(0, \xi) = 0$ and isothermal, i.e., $T_e(0, \xi) = T_i(0, \xi) = T_0$, where $T_0 = 6700$ K. The ionization degree $x$ is defined by a modified Saha formula (Somov et al. 1981). We also take into account the initial momenta delivered by the particles at injection (Brown & Craig 1984) by assuming $n(0, \xi_{\text{min}}) = P_B/m$, where $P_B$ is the sum of the momenta of all injected particles.

The initial distribution of a plasma density is defined as

$$ n(0, \xi) = n_{\text{min}} + h_0^{-1}(\xi - \xi_{\text{min}}), $$
where $n_{\text{min}} = 10^{10}$ cm$^{-3}$ and $h_0$ is the height scale,

$$h_0 = \frac{k_B [1 + x(T_0)] T_0}{\mu g_0}.$$  

(8)

The radiative losses rate $L(n, T_e)$ is described by the analytical expression

$$L_{n, T_e} = n^2 x L(T_e) + n L_H(n, T) \text{ erg cm}^{-3} \text{ s}^{-1},$$  

(9)

where the radiative loss function $L(T_e)$ is taken for the coronal abundances of elements in optically thin plasma (Cox & Tucker 1969) and $L_H(n, T)$ are the radiative losses in all hydrogen lines calculated for the optically thick atmosphere (Zharkova & Kobylnskij 1993).

The boundary conditions are defined as follows. (1) We assumed that there is no initial heat flux on the top boundary, i.e.,

$$\frac{\partial T_e(0, \xi_{\text{min}})}{\partial \xi} = \frac{\partial T_e(0, \xi_{\text{min}})}{\partial \xi} = 0.$$  

(2) The upper boundary is a free surface in the presence of the coronal pressure, i.e.,

$$\frac{\partial n(t, \xi_{\text{min}})}{\partial \xi} = \frac{4}{3 \pi m_p} \{ p(t, \xi_{\text{min}}) - p_{\text{cor}}[z(t, \xi_{\text{min}})] \},$$  

(10)

where $p(t, \xi_{\text{min}}) = n k_B (T_i + x T_e)$ and $p_{\text{cor}}[z(t, \xi_{\text{min}})] = n_{\text{min}} k_B [1 + x(T_0)] T_0$, where the ionization degree $x$ is defined by a modified Saha formula (Somov et al. 1981).

### 3.3. The Momenta Delivered by Beams and Hydrodynamic Shock

#### 3.3.1. The Momenta Delivered by a Proton or Electron Beam

The momentum $P_{e, p}$ delivered in pure collisions by an electron or proton beam with a spectral index $\gamma_{e, p}$ and a lower energy cutoff $E_{\text{low, } e, p}$ can be evaluated as (Zharkova & Gordovskyy 2005b)

$$P_{e, p} = \sqrt{2 m_{e, p} K \int_{E_{\text{low, } e, p}}^\infty E^{-\gamma_{e, p} + 0.5} dE},$$  

(11)

where $m_{e, p}$ is the electron or proton mass, $E_1$ is the lowest energy in the relevant particle spectrum (theoretical lower energy cutoff), and $K$ is the normalization constant that can be found from the total number of measured particles $N_{e, p}$.

$$N_{e, p} = K \int_{E_{\text{low, } e, p}}^\infty E^{-\gamma_{e, p}} dE = \frac{K}{\gamma} E^{\gamma + 1}_{\text{low, } e, p},$$  

(12)

where $E_{\text{low, } e, p}$ is the measured lowest energy of electrons or protons. Hence, without taking into account pitch angle scattering, the momentum delivered by a proton beam can be evaluated by substituting the constant $K$ found from $N_{e, p}$ into the equation for $P_{e, p}$ and performing the integration. This will result in the following:

$$P_{e, p} \simeq \sqrt{2 m_{e, p} N_{e, p} \frac{\gamma_{e, p}}{(\gamma_{e, p} + 0.5)} E_1^{-(\gamma_{e, p} - 0.5)}}.$$  

(13)

If we assume that $E_1 = E_{\text{low, } e, p}$, then the momentum delivered by electrons/protons without pitch angle scattering can be evaluated as

$$P_{e, p} \simeq \sqrt{2 m_{e, p} N_{e, p} \frac{\gamma_{e, p}}{\gamma_{e, p} + 0.5} E_{\text{low, } e, p}^{-0.5}}.$$  

(14)

It should be emphasized that this is the upper limit of the momentum carried downward to the photosphere by electrons or protons, since it is calculated without taking into account pitch angle scattering and wave dissipation for protons or Ohmic dissipation for electron, which can reduce its magnitude by a few factors (Gordovskyy et al. 2005). However, it allows the comparison of the momenta delivered by high-energy particles with those measured from the downward motions in Dopplergrams and from the TD diagrams.

#### 3.3.2. The Momentum Delivered by a Hydrodynamic Shock

Let us also evaluate the momentum delivered by a hydrodynamic shock using the simple formula

$$P_{\text{hd}} = \Sigma_{i=1} \rho v(t),$$  

(15)

where the summation is done over the time from 0 to $\tau$, where $\tau$ is a duration of the impact causing the seismic waves, $m$ is the mass of the plasma delivering the momentum related to the flaring area $A$ where the momentum is deposited, $V$ is a starting velocity of the plasma at the moment of impact, and $t$ is a duration of the impact.

For the known plasma mass density $\rho = n m$, where $n$ is the particle density per volume defined from hydrodynamic solutions, this equation can be rewritten as

$$P_{\text{hd}} = \Sigma_{i=1} \rho v(t) \approx \rho A v^2 r,$$  

(16)

where $\rho$ is an average density of the plasma delivering the momentum, $A$ is the flaring area where the momentum is deposited, $v$ is an averaged velocity of the plasma propagation at the moment of impact, and $\tau$ is the duration time of the impact.

### 4. RESULTS AND DISCUSSION

#### 4.1. The Momenta Delivered by Beams

Let us try to establish the agents delivering the momenta reported in Table 2 (§ 2.4) by investigating the parameters of high-energy particles associated with each source from the hard X-ray and $\gamma$-ray observations by CORONAS, INTEGRAL, and RHESSI in § 2.2.

**Source S1.**—For source S1, one has no $\gamma$-ray emission but only hard X-ray photon differential spectra (or mean flux) as presented in Figure 3 (two right columns), with an upper energy of 150 MeV and a lower energy cutoff of about 18 keV (third column, top; 11:02:00–11:03:00 UT; Kurt 2006, private communication). The photon spectral index in this plot was about $\delta_{\text{high}} = 3.5$–4.0 in the energy range 70 to 60 MeV and $\delta_{\text{low}} = 1.5$ for the energy range of 10–70 keV (Fig. 3). Since this was a very strong flare, we assume that the precipitating beam has induced a very strong electric field and its hard X-ray emission was dominated by the Ohmic energy losses (Zharkova & Gordovskyy 2005b, 2006). This assumes that the spectral index $\gamma$ of a precipitating electron beam has to be nearly the same as the index $\delta_{\text{high}}$ of the photon spectrum at higher energy.

The difference between the spectral indices $\delta_{\text{high}}$ and $\delta_{\text{low}}$ can provide us with the beam initial energy flux $F_0$ for the selected spectral index of an electron beam, i.e., for the beams with $\gamma$ varying from 3.5 to 5, the difference in the photon indices varies from 2.0 to 2.5. Hence, from Figure 12 (Zharkova & Gordovskyy 2005b) we can deduce the initial energy flux of beam electrons that can vary from $1 \times 10^{12}$ erg cm$^{-2}$ s$^{-1}$ for $\gamma = 3.5$ to $4 \times 10^{11}$ erg cm$^{-2}$ s$^{-1}$ for $\gamma = 5$ (Zharkova & Gordovskyy 2005b).

These fluxes can be carried out by electron beams with the initial densities of $1 \times 10^9$ and $6 \times 10^9$ cm$^{-3}$, respectively.
Let us calculate the momenta delivered to the photosphere by electron beams with such parameters using the technique described in § 3.3.1. For a flare area of about \(5.05 \times 10^{17}\) cm\(^2\), defined by the area of a downward Doppler motion (Fig. 4) in source S1, the momentum delivered to this area by the electron beam was about \(2 \times 10^{20}\) g cm s\(^{-1}\). Obviously, this is not sufficient to deliver the required momentum of \((3–4) \times 10^{22}\) as reported in Table 2 and so directly cause the ridge observed in the TD diagram for S1 (see § 2.4).

Sources S2 and S3.—Sources S2 and S3 appear close to the locations of hard X-ray emission and within the circle denoting \(\gamma\)-ray emission observed by RHESSI (Hurford et al. 2006). As was noted in § 2.2, the spectral indices of the proton energy spectra observed by INTEGRAL in phase B after 11:06:00 UT (from the ratios of \(^{12}\)C and \(^{16}\)O lines) vary from 3 to 3.8 (Kienzer et al. 2006), or by the RHESSI measurements (from the de-excitation line 2.22 MeV and positron annihilation line 511 keV) are \(2.8 \pm 0.4\) with a total number of protons observed estimated at about \(10^{33}\) (Share et al. 2004) and the lowest energy about 30 MeV, or \(\approx 4.8 \times 10^{-5}\) erg. However, this energy can be decreased to 2 MeV without affecting the 2.22 MeV and annihilation line emission (Share et al. 2004).

Then the momentum delivered by such a proton beam to the chromosphere, where the \(\gamma\)-emission is measured, can be about \(\sim 2.2 \times 10^{22}\) g cm s\(^{-1}\) for the lower energy of 30 MeV, and according to equations (12) and (14) increases as \((2\text{ MeV}/30\text{ MeV})^{-\gamma} 0.5\gamma / (\gamma + 0.5)\) to \(\sim 5.2 \times 10^{24}\) g cm s\(^{-1}\) for the lower energy of 2.0 MeV and \(\gamma = 3.0\). This range superbly covers those momenta derived in sources S2 and S3 (Table 2). Hence protons could be the agents in these two sources, delivering sufficient momenta to the region where MDI measures the Doppler velocities. Of course, as pointed out in § 3.3.1, the momentum evaluated from equations (12)–(14) provide the upper limit, since other proton or electron scattering mechanisms can slightly reduce the number of particles reaching a given depth from the top, depending on beam parameters. However for moderately hard beams, as reported for this flare (spectral index of 3.3), this difference is not very noticeable (Zharkova & Gordovskyy 2005b).

4.2. Simulated Heating Functions

Now let us compare the heating rates of the three kinds of particles considered in §§ 3 and 3.1. The timescale within which each kind of particle can reach the photosphere is about 1 s for electron beams, 2–5 s for proton beams, and 10–20 s for protons of separatrix jets for the standard loop length of \(10^7\) cm (Zharkova & Gordovskyy 2004; Gordovskyy et al. 2005). Therefore, the propagation time for each kind of particle is short enough to contribute to the ambient plasma heating and to form a shock or a lower temperature condensation, appearing as a result of the hydrodynamic response to these particle injection.

The heating rates simulated from the full kinetic approach are presented in Figure 7: curve A for an electron beam with initial energy flux \(F_0 = 1.4 \times 10^8\) erg cm\(^{-2}\) s\(^{-1}\), spectral index \(\gamma = 2\), and lower energy cutoff 16 keV; curve B for the separatrix jet protons with initial energy \(E_0 = 1\) MeV and initial energy flux of \(4 \times 10^{11}\) erg cm\(^{-2}\) s\(^{-1}\); curve C for an electron beam with initial energy flux \(F_0 = 10^{10}\) erg cm\(^{-2}\) s\(^{-1}\), spectral index \(\gamma = 5\), and lower energy cutoff 16 keV; and curve D for a proton beam with initial energy flux \(F_0 = 4 \times 10^{10}\) erg cm\(^{-2}\) s\(^{-1}\), spectral index \(\gamma = 1.5\), and lower energy cutoff 40 keV.

It can be seen that the heating by electron or proton beams with power-law energy distributions is strongly dependent on the initial beam parameters: softer and weaker beams deposit their energy mainly in the corona and upper chromosphere, while harder and more powerful beams deposit more energy deeper in the lower chromosphere (compare curves A and C for hard and soft electron beams and D for a soft proton beam; Zharkova & Gordovskyy 2005b; Gordovskyy et al. 2005).

Electron beams are considered to deposit their energy more evenly in depth than proton beams (compare curves A and C with D). Proton beams deposit the bulk of their energy via generation of KAWs with their following dissipation in Cherenkov resonance at the flaring atmosphere depths where their velocities are higher than the local Alfven velocities (Gordovskyy et al. 2005). It can be noted that the heating by KAWs induced by protons has two regions where this condition stands: in the upper corona because of their initial exponential distributions (the first curve B) and at the lower chromosphere because of reduction of the local Alfven speed and of the proton exponential distributions (the second, spikelike curve B).

The heating of the upper atmosphere by proton beams can be even more noticeable after Coulomb collisional losses are taken into account, which will make the proton distributions in the chromosphere even more exponential. While strongly affecting heating by proton or electron beams of the corona and upper chromosphere (before the column densities of \(10^{20}\) cm\(^{-2}\)), the collisions do not significantly change the heating of the lower chromosphere where Cherenkov resonance is dominant (Gordovskyy et al. 2005). Another heating mechanism considered for beam electrons is Ohmic dissipation in a self-induced electric field that contributes significantly to the heating of the coronal levels but again has not affected the lower atmosphere heating (Zharkova & Gordovskyy 2005b).

The effect of these heating functions on the hydrodynamic solutions is discussed below. In the heating functions we include collisional losses by both electron and proton beams, Ohmic losses only for an electron beam, and Cherenkov resonance for thermal-like protons. Two heating functions are considered: a pure electron beam and a proton beam combined with quasi-thermal jet protons.

4.3. Simulated Hydrodynamic Responses

In order to maximize a deposition at lower atmospheric levels, let us compare the hydrodynamic responses caused by a hard electron beam with \(\gamma = 3.5\) and the initial energy flux of \(10^{11}\) erg cm\(^{-2}\) s\(^{-1}\) (which is higher and harder than measured)
with those caused by proton beams/jets with spectral indices of about 3 and initial energy fluxes of $10^{12}$ erg cm$^{-2}$ s$^{-1}$, as deduced from the hard X-rays and $\gamma$-rays in § 2.2.

We simulate the hydrodynamics of a two-temperature plasma heated by either electrons or protons (power laws plus those with Maxwellian energy distributions) by solving the two energy equations (for electrons and protons), continuity and momentum conservation equations, and including the radiative cooling as described in § 3.2.

The variations of temperature, density, and macrovelocity simulated for the hydrodynamic responses are plotted for the electron beam with parameters derived from hard X-rays (Fig. 8, left) or for the mixed proton/jet beam with parameters derived from the $\gamma$-ray emission (Fig. 8, right).

The presented hydrodynamic results caused by beam electrons agree with those by Somov et al. (1981), Nagai & Emslie (1984), and Fisher et al. (1985a, 1985b, 1985c). For the intense hard beam, as deduced from the hard X-ray data from KORONAS (Kuznetsov et al. 2006), there is a noticeable decrease (rarification) of the total plasma density and a strong temperature increase in the corona, accompanied by explosive evaporation of the chromospheric plasma into the corona (macromotion upward) occurring in response to the beam injection.

Starting from the column density $2 \times 10^{19}$ cm$^{-2}$, a collisional stopping depth for lower energy electrons of 12 keV accepted in our simulations, a low-temperature condensation is formed moving as a shock with velocities of about 100–200 km s$^{-1}$, which are higher than the local sound velocity (Somov et al. 1981; Fisher Fig. 8.—Hydrodynamic responses of a flaring atmosphere caused by pure electrons (left) or by mixed proton and electron beams (right) with the parameters of protons deduced from $\gamma$-rays and electrons from X-rays from RHESSI and KORONAS. Top: Ambient electron temperatures. Middle: Densities. Bottom: Macrovelocities. The numbers on the graphs show the times in seconds after the beam injection.
et al. 1985). However, such a shock produced even by a powerful electron beam with the spectral index of about 3 appears rather high in the upper chromosphere between the column depths of \( (2 \times 10^{20}) \) and \( (2 \times 10^{25}) \) cm\(^{-2}\), as can be seen in Figure 8 (left).

These two motions of the ambient plasma (upward and downward) are reported in all the hydrodynamic simulations (Somov et al. 1981; Nagai & Emslie 1984; Fisher et al. 1985a, 1985b, 1985c) and widely investigated from the blue and redshifted spectral measurements in UV and H\(\alpha\) emission, respectively. For some events and some beam parameters these can be nearly equal (e.g., see Zarro et al. 1988), while for many other beams if the electron Ohmic losses are taken into account (Zharkova & Gordovskyy 2006) only the blueshifts could be observed without the noticeable red ones.

As can be seen from Figure 8, the hydrodynamic response to the injection of pure electron or mixed proton/jet beams are substantially different. The electron beam injected over 10 s produces a smaller (by factor 2–2.5) temperature increase in the corona (top left), a smaller (by an order of magnitude) density depression of the coronal plasma into the chromosphere (middle left), and smaller (by factor 2–2.5) evaporation velocities (bottom left) compared to those produced by mixed proton/jet beams (Figs. 8, right, and 9).

In addition, the mixed proton/jet beam forms the lower temperature shock, which is spread much deeper into the lower chromosphere between the column depths of \( (2 \times 10^{20}) \)–\( (8 \times 10^{21}) \) cm\(^{-2}\) (see Fig. 9 for a closer view of the shock in the first 100 s). The velocities of the shock induced by the mixed proton beam are also higher (by a factor of 2–2.5) than those induced by the pure electron beam. These macrovelocities induced by the proton beam decrease in the region with a column density of \( 5 \times 10^{21} \) cm\(^{-2}\) to a few km s\(^{-1}\) compared to those less than 1 km s\(^{-1}\) for the one induced by electrons. The momentum induced by this shock is transferred to the photosphere within a much shorter timescale, under 1 minute, because it is formed in much deeper and denser atmospheric levels. This is also confirmed by the temporal profile of the macrovelocity variations at the lower edge of the shock (the far right points in the distributions in Fig. 9) induced by proton beams showing an increase to a few km s\(^{-1}\) of the edge macrovelocities within a minute, which resembles those measured in Figure 5 (after the column depth of \( 10^{21} \) cm\(^{-2}\)).

The proton-induced shock deposits its momentum from the depths \( (5–8) \times 10^{21} \) cm\(^{-2}\) to very dense plasma beneath that is delivered with a velocity of about 2 km s\(^{-1}\) through about 120 km of the solar atmosphere before approaching the column depth of \( 4 \times 10^{23} \) cm\(^{-2}\) for Ni line region. The electron-induced shock is required to travel from the column depth of \( (2–5) \times 10^{20} \) cm\(^{-2}\), or about 350 km, with the same or a twice lower velocity, which will allow the momentum to reach the Ni region with a delay of 3–6 minutes.

4.4. The Region for Ni 6768 Line Formation

In order to understand the effect of the hydrodynamic shocks on the Doppler measurements in the Ni 6768 line by the MDI instrument, one needs to establish the line formation region. This can be done by using the full non-LTE simulations (without magnetic field effects) of the Ni line in the ambient plasma with the coronal abundance of elements and molecules (up to 23 in total are considered; the main ones are CO, C\(_2\), CH, and CN; Bruls 1993; Uitenbroek 2001; Zharkova & Kosovichev 2002). The ambient plasma temperature, density, and macrovelocities are described by the hydrodynamic solutions presented in § 4.3.

We consider two cases: the quiet Sun atmosphere outside sunspots (Fig. 10, top) before the beam onset, and the flaring atmosphere heated by beam electrons (Fig. 10, bottom). The contribution functions for the regions, where the Ni line 6768 is formed, are plotted by the gray curves with the black arrows marking the maximum contribution. The background contribution functions (for the continuum) are plotted by the second curves from the top with the upward-pointing arrows at the far right marking a region of the maximum continuum contribution around the Ni line. The total contribution functions for all elements are plotted by the second curves from the bottom. The dashed curves show the Planck contribution functions, and the middle curves present the mean intensity \( J \) from a given atmospheric level for the temperature distributions taken from Figure 8 (top left; time = 7 s after the beam injection).

The formation region for the Ni line at 6768 Å lies approximately within the column depths of \( (2.0–4.0) \times 10^{21} \) cm\(^{-2}\), or around 200 km for the quiet Sun (Fig. 10, top), which increases to \( (4.0–6.0) \times 10^{21} \) cm\(^{-2}\), or around 180 km, for the flaring atmosphere heated by beam electrons (Fig. 10, bottom), which agrees rather well with the estimations found from the previous non-LTE simulations (Bruls 1993; Zharkova & Kosovichev 2002).

Let us compare these column depths with those obtained for the lower temperature shocks simulated from the hydrodynamic responses to injection of electron or proton/electron beams as discussed in § 4.3. One can notice that the column depths for the Ni line region are closer to a hydrodynamic shock formed by the mixed proton/jet beam (Figs. 9 and 8, right). In addition, the shock velocities decrease to a few km s\(^{-1}\) toward the deeper density edge (the right ends of each curve in Fig. 9), and this decrease has a temporal profile of the lower edge velocities increasing from 0.1 km s\(^{-1}\) (at 1 s) to 2 km s\(^{-1}\) (at 50 s) and then decreasing back similarly to those measured by MDI (see Fig. 5).

As discussed above in § 4.3, this shock needs only about 60 s to reach the Ni region, which allows the detection of the seismic response nearly simultaneously with the hard X-rays, as reported for this flare in §§ 2 and 2.4. While the shock caused by the electron beam is formed much higher in a flaring atmosphere (Fig. 8, left), it can be measured in the Ni 6768 line, delayed by up to 6 minutes compared to the time of X-ray and \( \gamma \)-ray emission.
The shock caused by a pure electron beam (Fig. 8, left) with the beam parameters taken from Figure 3 has a density of about $5 \times 10^{12}$ cm$^{-3}$, an average macrovelocity about $1.8 \times 10^7$ cm s$^{-1}$, and a duration of about 100 s. This shock is formed at a depth of about $(2-5) \times 10^{20}$ cm$^{-2}$. The momentum still requires a timescale $>180$ s to be delivered to the Ni line formation region $(2-6) \times 10^{23}$ cm$^{-2}$. Then for source S1 with an area of about $5.05 \times 10^{17}$ cm$^{-2}$, the electron-formed shock can deliver a momentum of about $1.3 \times 10^{19}$ g cm$^{-1}$.

Evidently, the shock produced by a pure electron beam does not contain enough momentum to account for the seismic responses recorded in either source. In addition, a time delay of about 180–360 s is required for this shock to reach the region of the Ni line formation and to cause a delay in the seismic response appearance compared to the emission in hard X-rays and $\gamma$-rays.

On the other hand, the parameters of the proton-formed shock are much more relevant to an explanation of the momenta observed in the seismic sources S1, S2, and S3. This shock occurs much closer to the region where the Ni line is formed, and it contains much denser material (up to $10^{14}$ cm$^{-3}$) and higher macrovelocities, $(2-3) \times 10^7$ cm s$^{-1}$. By substituting these parameters and the areas of sources S1, S2, and S3 taken from Table 2 into equation (16), one can find that this shock can deliver a much higher ($>4.4 \times 10^{22}$ g cm$^{-1}$) momentum than that delivered by the electron-formed shock. The momentum induced by this shock is transferred to the photosphere within a much shorter timescale, under 1 minute, because it is formed in much deeper and denser atmospheric levels. Therefore, the magnitudes of the momentum carried by the shock caused by the mixed proton/jet beam, and the timescale within which it reaches the region of Ni line, are rather close to those deduced from the TD diagrams discussed in § 4.1 (Table 2) for all the seismic sources.

Since $\gamma$-ray emission by high-energy protons was observed by KORONAS only after 11:06:00 UT (Kuznetsov et al. 2006), when sources S2 and S3 appeared, one can assume that these sources are produced by a high-energy proton beam combined with the lower energy ($<200$ MeV) quasi-thermal protons of the separatrix jets. Together they can deliver momentum to the photosphere via hydrodynamic shock, to directly cause the observed seismic responses and energize ambient electrons to energies high enough for the hard X-ray and $\gamma$-ray emission observed at 11:06:00 UT in the third burst, as discussed in § 2.2.

For source S1 sufficient momentum can be delivered by a very high energy electron beam, which is reported to have energies of hundreds of MeV (Kuznetsov et al. 2006) and occurred at 11:02:00 UT in the first burst (Fig. 3), combined with lower energy ($<200$ MeV) quasi-thermal jet protons. Then the hydrodynamic response to such heating could lead to a shock formed slightly deeper in the flaring atmosphere than those for the electron beam from Figure 8, and slightly higher than for the protons. Within 3–4 minutes after the beam onset, the momentum caused by this hydrodynamic shock can reach the Ni region and cause the observed seismic waves discussed above, which explains the delay of about 3–4 minutes between the seismic response in source 1 and the hard X-ray emission in the first burst that started at 11:02:00 UT.

5. CONCLUSIONS

In the current paper we report the 11 sources with downward motions faster than 1 km s$^{-1}$ in the 2003 October 28 flare and the seismic waves in three of them (S1–S3) that were detected with the time-distance (TD) diagram technique. The three seismic sources started around 11:05:00–11:06:00 UT, and had slightly different downward (vertical) velocities and heights of ridges.
or horizontal velocities, pointing out to different agents causing them.

We investigate a few agents that may be able to deliver the required energy and momentum to the flaring atmosphere: power-law electron beams, power-law proton beams, and quasi-thermal protons with energies below 200 MeV occurring through acceleration by a super-Dreicer electric field in RCSSs on the top of a flaring atmosphere (Zharkova & Gordovskyy 2004, 2005a). Electron beams are assumed to deposit their energy in collisions and Ohmic dissipation, and proton beams in collisions and generation of kinetic Alfvén waves with their following dissipation in Cherenkov resonance (Gordovskyy et al. 2005).

The hydrodynamic responses to a precipitating power-law electron beam or to a proton beam mixed with the protons of separatrix jets are also investigated. The hydrodynamic response to the injection of the pure electron or mixed proton/jet beams are found to be substantially different. The electron beam injected over 10 s produces a smaller (by factor 2–2.5) temperature increase in the corona (top left), a smaller (by an order of magnitude) density depression of the coronal plasma into the chromosphere (middle left), and smaller (by factor 2–2.5) evaporation velocities (bottom left) compared to those induced by mixed proton/jet beams (Fig. 8, right, and Fig. 9).

In addition, the mixed proton/jet beam forms a low-temperature shock, which is spread much deeper into the lower chromosphere between the column depths of $(2 \times 10^{20})$ and $(8 \times 10^{21})$ cm$^{-2}$ (see Fig. 9 for a closer view of the shock in the first 100 s). The velocities of the shock induced by a mixed proton beam are also higher (by a factor of 2–2.5) than those induced by a pure electron beam. These macrovelocities induced by the proton beam decrease in the region of a column density of $5 \times 10^{21}$ cm$^{-2}$ to a few km s$^{-1}$, compared to those less than 1 km s$^{-1}$ for the one induced by electrons. In addition, the temporal profile of the macrovelocity variations at the lower edge of the shock (the far right points in the distributions in Fig. 9) induced by proton beams shows within a minute an increase to a few km s$^{-1}$ at the edge macrovelocity (at column depth above $10^{21}$ cm$^{-2}$), which resembles those measured in Figure 5.

The momenta and start times measured from the TD diagrams in sources S1–S3 are compared with those delivered to the photosphere by different kinds of high-energy particles with parameters deduced from hard X-ray and $\gamma$-ray emission, as well as by the hydrodynamic shocks caused by these particles.

The energetic protons (power laws combined with Maxwellian ones from the separatrix jets) are shown to deliver high enough momenta and to form hydrodynamic shocks much deeper in a flaring atmosphere than a pure electron beam. This allows the proton-formed shocks to travel shorter distances to the photosphere over less time, resulting in seismic waves occurring nearly simultaneously with the high-energy emission as observed in sources S2 and S3. The source S1 is likely to be associated with a hard power law electron beam mixed with the quasi-thermal protons of the separatrix jets.

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