Onset of Photospheric Impacts and Helioseismic Waves in X9.3 Solar Flare of 2017 September 6

Ivan N. Sharykin
Department of Physics, New Jersey Institute of Technology, Newark, NJ 07102, USA
sharykin@njit.edu

Alexander G. Kosovichev
Center for Computational Heliophysics, New Jersey Institute of Technology, Newark, NJ 07102, USA; sharykin@njit.edu

1 Center for Computational Heliophysics, New Jersey Institute of Technology, Newark, NJ 07102, USA; sharykin@njit.edu
2 Department of Physics, New Jersey Institute of Technology, Newark, NJ 07102, USA
3 Department of Space Plasma Physics, Space Research Institute of RAS, Moscow, 117997, Russia

Received 2018 April 10; revised 2018 July 14; accepted 2018 July 19; published 2018 August 31

Abstract

The X9.3 flare of 2017 September 6, was the most powerful flare of Solar Cycle 24. It generated strong white-light emission and multiple helioseismic waves (sunquakes). By using data from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory as well as hard X-ray (HXR) data from the KONUS instrument on board the WIND spacecraft, and Anti-Coincidence System on board the INTERGRAL space observatory, we investigate spatio-temporal dynamics of photospheric emission sources, identify sources of helioseismic waves, and compare the flare photospheric dynamics with the HXR temporal profiles. The results show that the photospheric flare impacts started to develop in compact regions in close vicinity of the magnetic polarity inversion line (PIL) in the preimpulsive phase before detection of the HXR emission. The initial photospheric disturbances were localized in the region of strong horizontal magnetic field of the PIL, and, thus, are likely associated with a compact sheared magnetic structure elongated along the PIL. The acoustic egression power maps revealed two primary sources of generation of sunquakes, which were associated with places of the strongest photospheric impacts in the preimpulsive phase and the early impulsive phase. This can explain the two types of helioseismic waves observed in this flare. Analysis of the high-cadence HMI filtergrams suggests that the flare energy release developed in the form of sequential involvement of compact low-lying magnetic loops that were sheared along the PIL.

Key words: Sun: chromosphere – Sun: corona – Sun: flares – Sun: magnetic fields – Sun: oscillations – Sun: photosphere

Supporting material: animation

1. Introduction

Energy release of solar flares can affect all layers of the solar atmosphere. The strongest events are accompanied by continuum emission from the photosphere and generation of helioseismic waves. The latter are also referred to as “sunquakes,” initially predicted by Wolff (1972) and Kosovichev & Zharkova (1995) and discovered by Kosovichev & Zharkova (1998) using Dopplergrams from Michelson Doppler Imager on board the Solar Orbital Heliometric Observatory. Sunquakes are observed in Dopplergrams as concentric waves spreading out from an initial photospheric disturbances that occurred during the impulsive phase of a solar flare. The basic information about sunquakes can be found in the reviews of Donea (2011) and Kosovichev (2014). Helioseismic events are usually associated with the appearance of white-light emission sources (see the statistical work of Buitrago-Casas et al. 2015) located close to sunquake sources as found from the helioseismic holography method (Lindsey & Braun 1997; Donea et al. 1999; Lindsey & Braun 2000).

There are several ideas about the physical mechanism of sunquake generation. One of the most popular scenarios for initiation of helioseismic waves is a beam-driven hypothesis assuming that accelerated electrons are the primary sunquake drivers and the reason for the white-light emission. In this scenario, the helioseismic waves are formed due to hydrodynamic impact caused by expansion of the chromospheric plasma heated by nonthermal charged particles accelerated in the corona and injected into the chromosphere (Kosovichev & Zharkova 1995). The numerical hydrodynamic modeling of the beam-driven thick-target theory (Kostiuk & Pikelner 1975; Livshits et al. 1981; Fisher et al. 1985; Kosovichev 1986; Mariska et al. 1989; Rubio da Costa et al. 2015) predicts formation of a chromospheric shock (also called “chromospheric condensation”) moving from the overheated chromospheric plasma into the cooler and denser photosphere. This leads to compression and heating of the photosphere, and generation of the white-light emission and helioseismic acoustic waves. The wave travels through the convective zone where they are reflected and appear as expanding ripples in the photosphere. In addition, a backwarming process can be a reason for sunquake generation (Donea et al. 2006). This mechanism assumes a sharp enhancement of UV and optical radiation flux from the chromosphere leading to overheating of the photosphere.

However, the plasma momentum can also be transferred in other ways, such as a sharp enhancement of the pressure gradient due to eruption of magnetic flux-rope (e.g., Zharkov et al. 2011, 2013) or by an impulse Lorentz force that can be stimulated by changing magnetic fields in the lower solar atmosphere (Hudson et al. 2008; Alvarado-Gómez et al. 2012; Fisher et al. 2012; Burtsева et al. 2015; Russell et al. 2016). Sharykin & Kosovichev (2015) and Sharykin et al. (2015) discussed that rapid dissipation of electric currents in the low atmosphere could also explain sunquake initiation. It is possible that different sunquake events are caused by different mechanisms.

To understand the physics of sunquakes and strong photospheric perturbations, one needs to observe the whole flare...
impulsive phase in detail to trace the appearance of photospheric impacts. In particular, it is important to study properties of the magnetic field in the areas of initial photospheric brightenings, and also compare with emission sources seen in other parts of electromagnetic spectrum, in particular, with the hard X-ray (HXR) emission produced by precipitating high-energy electrons. Observational data with high temporal and spatial resolution are needed to catch the initial photospheric brightenings and trace their development in the impulsive and, even, preimpulsive phases of solar flares.

Recently, Sharykin et al. (2017) used level-1 data from the Helioseismic and Magnetic Imager (HMI) on board Solar Dynamics Observatory (SDO; Scherrer et al. 2012), which represent filtergrams taken with different polarization filters across the FeI 6173 Å line the time cadence of ≈3.6 s by each of the two HMI cameras. The high temporal resolution allowed them to make a precise comparison between the HXR emission observed by Reuven Ramaty High Energy Spectroscopic Solar Imager (RHESSI), photospheric optical emission and sunquake sources of the X1.8 flare of 2012 October 23. It was reported that the initial photospheric emission sources were located in the vicinity of the magnetic field polarity inversion line (PIL), and that the time delay between the HXR and photospheric emission profiles did not exceed 4 s. This delay was consistent with predictions of the flare hydrodynamics RADYN models. However, the data indicated that the photospheric impact and helioseismic wave might be caused by the electron energy flux, which is substantially higher than that in the current flare radiative hydrodynamic models.

In this paper, we present an analysis of the X9.3 GOES class solar flare of 2017 September 6, which started approximately at 11:53:00 UT, and show that the initial photospheric impacts occurred in the flare preimpulsive phase. This cannot be explained by the standard thick-target flare model. This flare, which so far is the strongest event of 24 solar cycles, produced protons and caused the Ground Level Enhancement (GLE 72). It was located in active region NOAA 12673 with heliographic coordinates S09W42. The flare and associated eruption were studied by many authors in different aspects. For example, Verma (2018) and Yang et al. (2017) found that a combination of different types of magnetic field dynamics was responsible for the flare triggering. Analysis of the HMI data revealed magnetic flux emergence, sunspot rotation, and shear flows along the PIL.

The flare generated strong white-light emission and helioseismic waves traveling from large-scale photospheric disturbances seen in all HMI observables. The helioseismic responses of this flare were first detected by Kosovichev (2017) who noted an unusual feature: excitation of several sunquakes, probably by different mechanisms. This flare was located not far from the disk center, and in this case the sunquake signal on HMI Dopplergrams is not reduced due to projection effects, unlike in the X1.8 flare, which was near the solar limb (Sharykin et al. 2017).

The main goal of this work is to perform a detailed study of the photospheric impacts that produced strong sunquakes and white-light emission. For the analysis, we use the HMI data, including the standard level-2 HMI observables and the high-cadence level-1 HMI filtergrams, as well as the X-ray data that were available for this flare from the GOES satellite, the HXR/gamma-ray spectrometer Konus (Aptekar et al. 1995) on board the Wind spacecraft, and, also, from ACS on board the INTERGRAL (SPI) observatory (Vedrenne et al. 2003). Our first task is to trace dynamics of the photospheric emission sources relative to the magnetic field structure of the flare region, and, thus, to define the locations of the initial photospheric impacts. The second task is to compare spatial positions of the photospheric impacts seen in different HMI observables with the sunquake sources deduced from the helioseismic holography method. The third task is to compare time profiles of the photospheric emission sources (using HMI filtergrams) with the HXR time profiles in order to test the beam-driven hypothesis of photospheric flare perturbations.

Section 2 describes the relationship between the magnetic field structure of the flare region and impulsive sources of continuum emission and Doppler shift using HMI 45 s level-2 data. The temporal behavior of the sources is compared with the corresponding GOES soft X-ray (SXR) lightcurves, as well as with the HXR time profiles from KONUS/WIND and ACS/Integral. Section 3 is devoted to the analysis of helioseismic signals (sunquakes) from the flare region. It presents a time–distance analysis of the observed helioseismic waves and reconstruction of sunquake sources using the acoustic holography method. Section 4 presents an analysis of photospheric emissions using the HMI level-1 filtergrams to determine the precise timing of the photospheric impacts relative to the flare HXR signals from KONUS/WIND. The last section summarizes results and formulates conclusions.

2. Photospheric Impacts and X-Ray Emission

2.1. PIL and Distribution of Continuum Emission and Doppler-shift Sources

The X9.3 flare of 2017 September 6 was characterized by very strong photospheric impacts seen in all HMI observables. In this section, we analyze the line-of-sight (LOS) magnetograms, Dopplergrams, and continuum intensity maps taken by the HMI instrument with a cadence of 45 s and a spatial resolution of 1”. Figure 1 presents a sequence of the continuum intensity maps covering the preimpulsive and impulsive phases. These maps are reprojected onto the heliographic grid to remove the projection effect and demonstrate the true length scale of the flare impacts and their position relative to the magnetic field PIL from the LOS Magnetograms. We show only the longest PIL separating the main sunspots. Heliographic degrees are converted to Mm, neglecting slight distortions due to sphericity. The flare produced very strong perturbations that distorted the magnetograms and the PIL’s shape. So, the two PILs for preflare (blue curves) and postflare (cyan) times are presented in Figure 1.

One can see that the flare region is very complex. Several sunspots are located close to each other forming a 6-type configuration with an S-shaped PIL. The photospheric emission sources determined from the running difference of the continuum intensity maps are marked by red and orange contours. Red and orange colors correspond to positive and negative frame-to-frame changes, respectively. Images in Figures 1(a)–(c) correspond to the preimpulsive phase (before the start of HXR emission). One can notice in panel (b) that the initial perturbations develop from two brightenings located in the PIL. In the next 45 s (panel c), the perturbations expanded along the PIL in the form of two sheared flare ribbons on both sides of the PIL. Additional brightenings appeared in the southern part of the large sunspots. The largest spatial scale (the distance between the southern and northern remote sources) is
about 28 Mm. The distance between the initial brightenings along the PIL is about 10 Mm, and the distance between the photospheric ribbons across the PIL is 3 Mm. These observations suggest that small-scale sheared magnetic loops in the PIL region were activated during the initial preimpulsive energy release with subsequent involvement of a large-scale magnetic structure. It is also worth noting that flare ribbons shown in panel (c) are very structured with many emission cores. The
45 s HMI data allow us to separate the photospheric flare sources in time and space. However, analysis of high-cadence HMI filtergrams in the Section 4 will show more details.

During the impulsive phase (Figures 1(d)–(i)), the emission sources moved along the PIL in the southern direction, probably, reflecting involvement of new magnetic loops into the flare energy release process. At the same time, continuum emission of the initial brightenings started to decrease (marked by orange contours).

Figure 2 demonstrates HMI Dopplergrams for the same time moments as in Figure 1. The strong photospheric impacts are revealed as compact white and black patches. They are also highlighted by red and blue contours corresponding to positive (downward) and negative (upward) Doppler velocities with magnitudes of 3 km s\(^{-1}\). The highest velocity magnitudes were up to 14 and 8 km s\(^{-1}\) for downward and upward velocities, respectively. However, these values may not accurately characterize real plasma velocities. Because of strong distortion of the Fe I line profile (observed by HMI), the Doppler-shift measurements in such places may be incorrect. Nevertheless, the high Doppler-shift values indicate places of strong photospheric impacts, and help to detect sources of helioseismic waves (e.g., Kosovichev 2014). The general Doppler velocity response was mostly downward that is in accordance with the idea of a downward moving shock producing the photospheric impact and helioseismic waves.

In the preimpulsive phase (Figures 1(a)–(c)), the initial velocity perturbations were located very close to the PIL. Comparing Figures 2 and 1 frame by frame, one can find that the continuum intensity changes correspond to the Doppler velocity impacts. However, it should be kept in mind that we compare time differences (for continuum intensity) with the usual HMI frame (Dopplergram). However, there are some differences between the Dopplergrams and intensity variation maps (which may be partly due to the 22.5 s time difference). For example, in the preimpulsive phase (panels c) the Doppler perturbations were located at the edges of the continuum intensity ribbons. Panel (d) (beginning of the impulsive phase) revealed that the photospheric impacts deduced from the Dopplergrams located closer to the PIL than the intensity perturbations. Moreover, the strongest impact was located directly in the PIL according to the Dopplergram. The subsequent frames e–i from both data sets show similar strongest photospheric impacts.

2.2. Comparison of the Photospheric Signals and HXR Time Profiles

In this subsection, we compare the photospheric flare signals from HMI, averaged through the field of view (FOV) shown in Figures 1 and 2, with the SXR and the HXR data. Figure 3 shows a comparison between the HMI observables (shown as step-wise functions) and the SXR and the HXR time profiles.

From Figure 3(a), it follows that the total HMI continuum intensity flux varies in accordance with the lightcurves of the GOES channels 0.5–4 and 1–8 Å. The time derivatives (Figure 3(b)) also fit each other. The long duration of the photospheric continuum and SXR emissions indicates that they are of thermal origin. However, the SXR emission comes from the hot coronal plasma while the HMI continuum emission can come only from the relatively low-temperature photospheric plasma. The temperature and emission measure of the SXR emitting plasma (calculated in the single-temperature approach) is plotted in panels (e) and (f), respectively. The highest temperature of 29 MK was during the impulsive phase when the peak emission measure was about 3.6 × 10\(^{26}\) cm\(^{-3}\).

The impulsive phase of this flare was not observed by RHESSI and FERMI spacecraft. Therefore, we used the HXR data from the HXR/gamma-ray spectrometer KONUS (Aptekar et al. 1995) on board WIND spacecraft, and, also, from the ACS on board the INTERGRAL (SPI) space observatory (Vedrenne et al. 2003).

The KONUS/WIND is an experiment devoted to the study of gamma-ray bursts and solar flares. It consists of two NaI(Tl) detectors observing correspondingly the opposite celestial hemispheres and is sensitive to all incoming HXR and gamma-ray emissions. The instrument operates near Lagrange point L1, so it does not suffer from “nights,” and has a very stable background. The instrument works in two modes: waiting and triggered mode. In the first mode, the count rate lightcurves are available in three wide energy channels G1 (18–70 keV), G2 (70–300 keV), and G3 (300–1160 keV) with a time cadence of 2.944 s. Switching to the triggered mode occurs at a statistically significant excess of 9σ above background in the G2 energy channel. In the triggered mode, the count rates are measured in the same three channels with a varying time resolution from 2 to 256 ms and with the total duration of 250 s. The KONUS/WIND data have been used in application to solar flares (e.g., Fleishman et al. 2016; Lysenko et al. 2018). The HXR count rate from KONUS/WIND in G2 channel for our flare is plotted in Figure 3(c). This count rate is corrected for the time delay between the L1 point and the Earth.

The ACS instrument is a set of BGO crystals viewed by photomultipliers. Due to the large effective area of 0.3 m\(^2\), the ACS is a very sensitive instrument to all HXR/gamma-ray emissions in the energy range \(\geq 100\) keV coming from all directions. The time resolution of the ACS is 50 ms. The SPI satellite has a very eccentric orbit outside the radiation belts. Thus, the radiation background is also quite stable on flare timescales. The ACS is not a solar-dedicated instrument, but its data have been used for solar flare studies (e.g., Struminsky & Zimovetz 2010; Zimovets & Struminsky 2012). The HXR count rate from ACS is shown in Figure 3(d).

The HXR data from both instruments are compared with the integral Doppler velocity responses in Figures 3(c)–(d). The HXR time profiles are characterized by three major impulses, the approximate duration of which was 30–50 s. In addition, the time profiles reveal fine temporal structuring of these impulses. Total duration of the HXR phase was about 150 s. Comparing the peak magnitudes in the different energy ranges we conclude that the first two peaks were harder in terms of the X-ray emission spectra than the third one which corresponds to the peak of time derivatives of the SXR lightcurves from GOES.

In this respect it is worth noting that the SXR and HXR time profiles do not follow the Neupert (1968) law. This may be related to the fact that we consider the high-energy data, above 70 keV. For lower energies there might be better correspondence.

The piece-wise plot in Figure 3(c) demonstrates temporal evolution of the averaged Doppler velocity changes (using the running time differences of Dopplergrams) for the region where the absolute value of velocity variations were higher than 1 km s\(^{-1}\). This value was selected arbitrary to define regions of the strong photospheric flare energy release where the highest
Fe I line Doppler shifts and distortions (in the case of incorrect velocity determination) occurred. One can see that the Doppler velocity perturbations were already pronounced (up to $3 \text{ km s}^{-1}$) in the preimpulsive phase during the first three HMI frames before the first HXR pulse. Then, the highest Doppler velocity was during the first two HXR pulses.

Figure 2. Series of HMI Dopplergrams (black–white background images) projected onto the heliographic coordinates for the same moments as in Figure 1. Red and orange contours correspond to positive and negative Doppler velocities with magnitudes of $3 \text{ km s}^{-1}$. Blue and cyan lines show the main (longest) PIL from HMI LOS magnetograms for two time moments: before (11:30:04 UT) and after (12:59:19 UT) flare.
However, the largest area (Figure 3(e)) of regions with the Doppler velocity changes higher than 1 km s$^{-1}$ was achieved at the time of the softer third HXR pulse.

The average Doppler velocity (Figure 3(d)) was calculated by averaging over the regions where the absolute values of velocity were higher than 3 km s$^{-1}$. This value is also arbitrary to emphasize the regions of the strongest photospheric impacts. Both, the downward and upward velocities were the most intensive also around the first two HXR peaks. The same temporal dynamics was observed for the Doppler perturbation area (Figure 3(e)). However, strong Dopplergram perturbations were also observed after the third HXR peak.

From Figure 3(d), we also found that the plasma temperature deduced from the GOES data had a peak around the HXR peaks, corresponding to the time derivatives shown in panel (b) of Figure 3. Thus, the coronal plasma heating was simultaneous with the precipitation of nonthermal electrons into the dense layers of the solar atmosphere and the rise of the photospheric continuum emission.

3. Helioseismic Flare Signals

To analyze helioseismic waves and their sources, we used the time series of running differences of HMI Dopplergrams remapped onto the heliographic coordinates and tracked with

---

**Figure 3.** (a) The total HMI continuum flux (blue) from the flare region (integrated over FOV of images in Figure 1) as a function of time and the soft X-ray lightcurves in two GOES channels of 0.5–4 Å (red) and 1–8 Å (black). (b) Time derivatives of the total HMI continuum flux and GOES lightcurves. (c) Time profiles of KONUS/WIND count rate in the energy range of 0.4–30 MeV (black) and the mean HMI Doppler velocity calculated for regions with $|v| > 1$ km s$^{-1}$ (blue). (d) The ACS/INTEGRAL HXR data (above 150 keV) and the mean HMI Doppler velocity (with amplitudes higher than 3 km s$^{-1}$). Blue and cyan colors correspond to positive and negative Doppler velocities, respectively. (e) Temporal profiles of the total area of regions with Doppler velocity variations higher than 1 km s$^{-1}$ (blue and cyan lines) and the flare temperature calculated from the GOES data (black). (f) Temporal profile of the total area of regions with the Doppler velocity amplitude higher than 3 km s$^{-1}$ (blue and cyan lines) and the flare emission measure calculated from the GOES data.
solar rotation. To isolate the wave signal from convective noise we applied a Gaussian frequency filter with a central frequency of 6 mHz and width of 2 mHz to each pixel of the Dopplergram differences.

The sunquake event was observed as a set of circular shaped waves spreading out from the region of the flare Dopplergram disturbances described in the previous section. An example of the flare disturbance and the sunquake wave is shown in Figures 4(c), (d). The time–distance (TD) diagrams for this wave is shown in Figures 4(a), (b). Two red lines show the orientation of the image slice, along which we calculated the diagram by averaging across this slit. The bands were oriented perpendicular to the wave front, and were 20 pixels wide to increase the signal-to-noise ratio. We present two time–distance diagrams (a) calculated from the nonfiltered and (b) filtered around 6 mHz time differences of Dopplergrams. The first plot is noisier but allows us to better estimate the sunquake initiation time without temporal uncertainty connected with the finite frequency range of the bandpass filter. The theoretical time–distance relation calculated in the ray approximation for a standard solar interior model of Christensen-Dalsgaard et al. (1993) is marked by the dashed curve in the TD diagram in Figure 4(b). The position of the wave ripples in the TD diagram matches the theoretical model. Thus, the observed wave was generated in the source corresponding to the Dopplergram disturbance.

To reconstruct the two-dimensional structure of the seismic source, we used the helioseismic holography method (Lindsey & Braun 1997; Donea et al. 1999; Lindsey & Braun 2000). This approach uses a theoretical Green function of helioseismic waves to calculate the egression acoustic power corresponding to the Doppler velocity perturbations. The Green function is calculated in the ray approximation, and the time sequence of HMI Dopplergrams is used as input for the helioseismic holography...
method. Integration of the Doppler signal is made for a pupil in the radii range of 10 and 50 Mm, which is selected according to the time–distance diagram (Figure 4(a)) showing the largest wave amplitude. The egression acoustic power map made in the frequency range of 5–7 mHz is shown in Figures 5(a)–(d) by red contours. We calculated this map by summing the egression power snapshots within the time interval found from the uncertainty principle $\Delta t \sim 1/\Delta \nu \approx 500$ s, where $\Delta \nu = 2$ mHz. This time interval corresponds to the appearance of the strong Doppler velocity perturbations. The egression power map is compared with four different Dopplergrams: two for the preimpulsive phase (Figures 5(a) and (b)) and two for the impulsive phase (Figures 5(c) and (d)). The PIL plotted in these panels was determined for the vertical magnetic field component using the HMI vector magnetogram reprojected onto the heliographic grid.

The egression power map shows a complex distribution of helioseismic sources that were located in the close vicinity to the PIL. There are two regions of generation of the helioseismic waves: northern and southern groups shown by two yellow circles in Figure 5(a). Several sources (northern group) are located in the same place as the initial perturbations observed during the preimpulsive phase and the first HXR peak (Figure 3). The helioseismic waves were possibly generated in the late preimpulsive phase at the start of the first HXR pulse. However, we cannot confirm this from the acoustic...
egress map because it is averaged over the whole impulsive phase. The southern helioseismic sources were located in the same place as the photospheric perturbations observed around the second and third HXR peaks. Thus, one can conclude that the helioseismic waves were generated during the whole impulsive phase and probably even in the preimpulsive phase. Perhaps the superposition of the helioseismic waves excited during the last two HXR peaks can explain the unusually long wavelength of the southward helioseismic wave (Kosovichev 2017).

The temporal profile (Figure 5(e)) of the egression acoustic power are calculated for the entire flare region (gray background histogram), as well as the northern (black histogram) and southern (blue histogram) groups of acoustic sources. The temporal profiles reveal a maximum of acoustic power for the flare region and the southern acoustic sources two minutes after the third HXR peak. In the case of the northern sunquake sources, the acoustic emission reached its maximum between the time moments of the most intense two HXR peaks. Thus, the acoustic emission in the different parts of the flare region was not synchronized that is in accordance with the displacement of the flare energy release site observed in the HMI intensity maps (Figure 1). The power started to increase in the preimpulsive phase. However, we can conclude that the most efficient generation of helioseismic waves was definitely during the precipitation of nonthermal electrons into the lower layers of solar atmosphere.

4. Precise Timing of Photospheric Impacts from HMI Level-1 Data

The HMI produces data by scanning the magneto-sensitive FeI line (6173 Å) at six wavelength positions across the line profile (Couvidat et al. 2016). There are two cameras producing a series of filtergrams with the pixel size of 0.5 in linear polarization (Camera 1) and in right and left circular polarizations (Camera 2). The filtergrams from both cameras (level-1 data) are used to reconstruct the full Stokes profiles. To calculate the LOS magnetograms, Dopplergrams, and continuum intensity (level-2 data), only Camera 2 is used. We use the original filtergram data in the disk coordinates from both cameras to achieve a high temporal resolution in order to investigate dynamics of the photospheric flare emission sources. The time cadence of filtergrams from each camera is 3.6 s. Previously, HMI filtergrams were applied to study a limb flare in the works of Saint-Hilaire et al. (2014) and Martínez Oliveros et al. (2014). Sharykin et al. (2017) presented an analysis of the X-class flare of 2012 October 23, which produced strong sunquakes. A detailed description of how to use the filtergrams for analysis of photospheric emission sources with high temporal resolution can be found in their paper. Here we present only a brief description of the filtergram analysis technique.

To identify the flare signals using the HMI level-1 data, we subtract a preflare filtergram from the filtergrams taken during the impulsive phase for the same wavelength and polarization. This allows us to detect changes in the flare region with high temporal resolution. The value in each pixel is calculated as \((I - I_0)/I_0\), where \(I\) is the pixel value for a flare filtergram, and \(I_0\) is the corresponding preflare value. We decided not to perform frequency filtering of the filtergram lightcurves to remove the variations caused by the line scanning as was done in the paper of Sharykin et al. (2017) because the photospheric signal was sufficiently strong in the flare emission sources. To demonstrate the development of the photospheric emission, we plot three filtergrams (white–black features) for 35 s of the preimpulsive phase (Figure 6) and three filtergrams for 80 s of the impulsive phase (Figure 7), and compare these with the maps of the horizontal and vertical magnetic field strength. To highlight the emission sources we also plotted black contours with 20%, 40%, 60%, and 80% levels relative to the maximal pixel value in the underlying image. Red contours in the top panels (a)–(c) of both figures mark the horizontal magnetic field strength of 1.5, 2, and 2.5 kG. The same levels of the vertical magnetic field are shown by red contours in the bottom (d)–(f) panels. The PIL is shown by blue lines. The magnetic field maps are derived from the HMI vector magnetograms with the time cadence of 720 s and, thus, the red and blue contours are the same in all panels. Only the back contours showing the continuum emission sources change during the selected time intervals.

The first photospheric emission in the preimpulsive phase was generated from two compact distant sources (Figure 6(a)) in the PIL. It seems that these sources are associated with a magnetic structure elongated along the PIL. The subsequent filtergrams (Figures 6(b), (c)) reveal emission in the PIL from a region of a very strong magnetic field (up to 3 kG), which is mostly horizontal. Positions of the strongest photospheric disturbances in the preimpulsive phase correspond to the northern region of sunquake generation. It is worth noting that the observed photospheric emission comes from numerous brightenings in the PIL, probably due to fragmented flare energy release.

Transition from the preimpulsive phase to the impulsive phase is clearly seen from the HMI filtergrams (Figure 7(a)) as the appearance of new brightenings along the PIL, south relative to the initial impacts. The strongest emission sources in Figures 7(b) and (c) are located about five arcsec from the PIL where the magnetic field is predominantly vertical. The location of the strongest brightenings is close to the southern complex of acoustic egression sources.

In Figure 8, we compare the filtergram lightcurves from four characteristic flare points (shown by red crosses in panels (a) and (c)) with the HXR time profiles. These points were selected to characterize the dynamics of continuum emission in the vicinity of the photospheric impacts observed during the preimpulsive (points 1 and 2, panel b) and impulsive (points 3 and 4, panel d) phases. The filtergrams corresponding to the preimpulsive and the impulsive phase are shown in panels (a) and (c), respectively. The resulting lightcurves are compared with the KONUS/WIND HXR time profile (blue line) in the energy range of 70–300 keV. This comparison reveals that the photospheric emission during the first and second HXR peaks were associated with points 1 and 2, appeared during the preimpulsive phase. Points 3 and 4 generated emission during the last HXR pulse. Thus, the flare continuum emission was sequentially generated along the PIL starting from places of strong horizontal magnetic field in the preimpulsive phase and finishing in sunspot areas of predominantly vertical magnetic field.

From the analysis of the HMI filtergrams, one can conclude that activity in the preimpulsive phase and initial impulsive phase was associated with energy release in a compact sheared magnetic structure elongated along the PIL with strong horizontal magnetic field. Subsequently, the energy release occurred in a larger magnetic structure sheared along the PIL and the footpoints located in areas of predominantly vertical magnetic field. The observed emission sources are very dynamic, compact and fragmented. Two main flare regions producing sunquakes were associated with the photospheric
emission sources seen in the preimpulsive and impulsive phase, respectively. This can explain the two types of helioseismic waves detected by Kosovichev (2017) in this flare, but the excitation mechanism is still unknown. It requires high-resolution spectro-polarimetric data with cadence higher than it is currently available from HMI to determine the physical conditions in photospheric emission sources.

5. Discussion and Conclusions

We presented a study of the X9.3 solar flare (SOL2017-09-06), which revealed strong white-light emission and generation of helioseismic waves (sunquakes). This study focused on three tasks: (1) investigate spatio-temporal dynamics of photospheric emission sources; (2) identify sources of helioseismic waves and compare them with the photospheric impacts; and (3) compare dynamics of photospheric emission with HXR temporal profiles. To perform these tasks, in addition to the standard (level-2) HMI observables obtained with 45 and 135 s cadence we used high-cadence (3.6 s) HMI filtergrams (level-1 data). This allowed us to localize initial photospheric brightenings, determine their relationship to the HXR pulses observed with high temporal resolution by the KONUS/WIND and ACS/INTEGRAL instruments, and relate the energy release events to sources of the helioseismic waves.
The main results can be summarized as follows:

1. The photospheric flare impacts started to develop in compact regions in close vicinity of the magnetic PIL in the preimpulsive phase before detection of the HXR emission. The initial photospheric disturbances were localized in the region of strong horizontal magnetic field of the PIL, and thus are likely associated with a compact sheared magnetic structure elongated along the PIL.

2. The acoustic egression power maps revealed two primary sources of generation of sunquakes, which were associated with places of the strongest photospheric impacts observed in the preimpulsive phase and the early impulsive phase. Thus, we have found evidence of initiation of helioseismic waves during the preimpulsive phase prior to the HXR impulse, and thus before precipitation of high-energy electrons in the low atmosphere. These two sunquake sources can explain the two types of helioseismic waves described by Kosovichev (2017).

3. Analysis of the high-cadence HMI filtergrams suggests that the flare energy release developed in the form of sequential involvement of compact low-lying magnetic loops that are sheared along the PIL. The photospheric emission from different flare points was associated with different HXR bursts. Thus, the particle acceleration process and corresponding photospheric impacts are

Figure 7. Same as in Figure 6 for three moments during the flare impulsive phase.
associated with spatial fragmentation of the flare energy release.

The research was supported by the NASA Grants NNX14AB68G and NNX16AP05H, and a grant of the President of the Russian Federation for the State Support of Young Russian Science PhDs (MK-5921.2018.2). The research is also partially supported by the Russian Foundation of Basic Research (RFBR, grant 18-02-00507). The observational data are courtesy of NASA/SDO, HMI, GOES, KONUS/WIND, and ACS/INTEGRAL science teams.

**Figure 8.** Panels (a) and (c): the flare emission sources (grayscale features) from the HMI filtergrams for two moments of time during the impulsive phase. The PIL is marked by blue color. Panels (b) and (d): the photospheric emission lightcurves (black for HMI Camera 1 and red for Camera 2) at four different points marked by red crosses in panels (a) and (c), and the KONUS/WIND count rate (blue) in the energy range of 0.4–30 MeV measured from the whole Sun.

**ORCID iDs**

Ivan N. Sharykin [https://orcid.org/0000-0002-5719-2352](https://orcid.org/0000-0002-5719-2352)
Alexander G. Kosovichev [https://orcid.org/0000-0003-0364-4883](https://orcid.org/0000-0003-0364-4883)

**References**

Alvarado-Gómez, J. D., Buitrago-Casas, J. C., Martínez-Oliveros, J. C., et al. 2012, *SoPh*, 280, 335
Aptekar, R. L., Frederiks, D. D., Golenetskii, S. V., et al. 1995, *SSRv*, 71, 265
Buitrago-Casas, J. C., Martínez Oliveros, J. C., Lindsey, C., et al. 2015, *SoPh*, 290, 3151
