DYNAMICS OF ELECTRIC CURRENTS, MAGNETIC FIELD TOPOLOGY, AND HELIOSEISMIC RESPONSE OF A SOLAR FLARE

I. N. SHARYKIN$^{1,2}$ AND A. G. KOSOVICHEV$^{1,3,4}$

$^1$ Big Bear Solar Observatory, New Jersey Institute of Technology, Big Bear City, CA 92314, USA
$^2$ Space Research Institute (IKI) of the Russian Academy of Science, Russia
$^3$ Stanford University, Stanford, CA 94305, USA
$^4$ NASA Ames Research Center, Mountain View, CA 94035, USA

Received 2015 January 21; accepted 2015 June 3; published 2015 July 17

ABSTRACT

The solar flare on 2011 July 30 was a moderate M9.3 class flare, but it made a strong photospheric impact and produced a “sunquake,” which was observed with the Helioseismic and Magnetic Imager on board NASA’s Solar Dynamics Observatory. In addition to the helioseismic waves, the flare caused a large expanding area of white-light emission and was accompanied by the rapid formation of a sunspot structure in the flare region. The flare produced hard X-ray (HXR) emission less than 300 keV and no coronal mass ejection (CME). The absence of CME rules out magnetic rope eruption as a mechanism of helioseismic waves. The sunquake impact does not coincide with the strongest HXR source, which contradicts the standard beam-driven mechanism of sunquake generation. We discuss the connectivity of the flare energy release with the electric currents dynamics and show the potential importance of high-speed plasma flows in the lower solar atmosphere during the flare energy release.

Key words: Sun: flares – Sun: helioseismology – sunspots – Sun: X-rays, gamma rays

1. INTRODUCTION

The flare energy release is usually accompanied by magnetic reconnection, dissipation, and eruptions of magnetized plasma. The magnetic restructuring is observed in the form of arcades of magnetic loops with reducing shear, changes of the strength and geometry of photospheric magnetic fields, erupting magnetic structures, and so on. Sometimes, the magnetic topology of the flare energy release site can be very complicated due to a complex interaction between magnetic fields rooted in multipolar active regions. Despite the complexity, all flares are accompanied by standard physical processes like particle acceleration, plasma heating of up to several MK, and plasma motion. The standard flare model (Sturrock 1989) assumes that the flare energy release processes are caused by magnetic reconnection in the corona, but the idea of flare initiation in the lower solar atmosphere has recently become popular because of new observational evidence of electric current intensification in the photosphere (e.g., Fletcher et al. 2011). Physically, the lower solar atmosphere significantly differs from the corona. The low atmosphere is characterized by partially ionized plasma, higher plasma $β$, and turbulent motions during solar flares. The works of Vainshtein et al. (2000) and Leake et al. (2012) show the complexity of magnetic reconnection in the chromospheric plasma and reveal a fast reconnection regime, with a rate independent of the plasma resistivity. Generally, the physical processes in the chromospheric conditions are not well-understood, and thus will be an important topic of future theoretical and observational studies. The current research is devoted to the observational study of flare processes in the lower solar atmosphere.

In this work, as a case study we present observations and analysis of a moderate M9.3 class flare that reveal several significant perturbations in the low atmosphere. The flare generated helioseismic waves, caused a large expanding area of continuum emission, and was accompanied by a rapid formation of a sunspot structure in the flare region. The flare produced hard X-ray (HXR) emission with energies up to $\sim$300 keV, but no coronal mass ejection (CME), and no type II and type III radio bursts. This indicates that the flare energy release was probably confined in the lower atmosphere in closed magnetic structures. The absence of significant CME and type II radio burst rules out the magnetic rope eruption as a mechanism of helioseismic waves.

Helioseismic waves, known as “sunquakes,” can be generated by several mechanisms: momentum transfer due to heating of the chromospheric plasma by accelerated energetic charged particles (Kosovichev & Zharkova 1995), impulsive Lorentz force (Fisher et al. 2012), pressure gradient due to flux rope eruption (Zharkov et al. 2013), and rapid dissipation of electric currents (Sharykin et al. 2014). However, the precise mechanism of sunquakes is still unknown (for a recent review, see Kosovichev 2014). The main goal of this work is to trace the plasma dynamics and magnetic field changes in the solar atmosphere, as well as possible agents of the flare energy release and sunquake initiation for this particular flare. We use the Solar Dynamics Observatory (SDO)/Helioseismic and Magnetic Imager (HMI) data (Scherrer et al. 2012) to determine the flare region magnetic field topology, estimate electric currents, and investigate the sunquake. X-ray data from the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite (Lin et al. 2002) are used to calculate the parameters of accelerated particles, and estimate their impact in the low chromosphere.

2. GENERAL CHARACTERISTIC OF THE FLARE

The M9.3 flare on 2011 July 30 occurred in the active region NOAA 11261, which had a $δ$-type magnetic configuration. According to the GOES-15 soft X-ray (SXR) data (Figure 1-bottom), the flare started at 02:04 UT, reached its maximum at 02:09 UT, and ended at about 02:30 UT. The RHESSI observations (Figure 1-top) show the presence of the X-ray emission up to 300 keV, reaching its maximum at 02:08 UT.
According to the Learmonth and Culgoora radio observatories, there were no type II radio bursts. This indicates the absence of significant shock waves, which could be associated with erupting magnetic structures. There was no recorded CME, which indicates the non-eruptive nature of the event. The radio data also indicate the absence of type III radio bursts, thus indicating a closed geometry of magnetic field lines in the flaring region.

The Atmospheric Imaging Assembly (AIA) on board SDO (Lemen et al. 2012) observes the Sun with a time cadence of 45 s and a spatial resolution of 1″, pixel size 0.6″. In Figure 2 we show the AIA images during and after the flare, illustrating the reconfiguration of ribbon-like structures in the AIA 304 Å channel (log T = 4.92). This reconfiguration probably corresponds to a reduction of the magnetic shear during the flare. In the AIA 94 Å channel (log T = 6.86), we observe the formation of hot large-scale loops.

The flare impact located in the vicinity of the magnetic field polarity inversion line (PIL) is also detected in all HMI observables (Figure 3). We will discuss the HMI observations in the next sections.

3. CONTINUUM EMISSION AND FLOW PATTERN IN THE FLARE REGION

The flare produced a strong continuum emission observed in the HMI data (Figures 3(b) and (c)). The western source originated near PIL and expanded in the west direction (Figure 3(c)). This expansion is clearly shown by the images showing the time derivatives of HMI continuum intensity on Figure 3(b), where white color corresponds to the growth of the continuum intensity, while black color means the decreasing intensity. The peak of the HMI continuum intensity (Figure 3(c)) averaged over the flare region (the dashed box in Figure 3) has a 2 minute delay relative to the HXR maximum (Figure 1-top) and a maximum of the growth of HMI continuum intensity (Figure 3(b)). The amplitude of white-light emission enhancement above the quiet Sun emission background is not very large and is seen in Figure 3(c) at 02:09:19 UT as a diffuse emission source near the PIL, where we observed the sunquake initiation. The estimated velocity of the HMI continuum signal expansion is ~30–40 km s^{-1}, which is higher than the local sound speed ~10 km s^{-1} and can be comparable to the magneto-acoustic speed of ~20 km s^{-1}.

We also show in Figure 3 the line of sight (LOS) velocity structure by contours. The velocity variations are revealed in the images of the time derivatives of Doppler velocity (Figure 3(a)), where white color corresponds to the growth of the flow speed, while black color indicates the decreasing speed. The most intriguing feature is the strong upflows reaching 3.6 km s^{-1} in the vicinity of PIL (the speeds of the upflows are shown by red contours). These flows are long-lived structures seen before the flare (see Figure 4), so they cannot be artifacts due to the impulsive variations of the line profile caused by the flare. We suppose that the impulsive variations of the Fe I emission line profile can only occur during the impulsive phase of the flare when we observe HXR emission. Before the flare, we did not observe evidence of impulsive energy release, thus the Fe I emission line is assumed to be not distorted and thus HMI measurements are reliable. During the most intensive HXR emission, we observe sharp changes in the Doppler speed. Such impulsive variations may be associated with the rapid variations of the line profile and in this case the corresponding Doppler speed variations are difficult to estimate. After the flare impulsive phase, the upflow region elongated along PIL is divided into two upflow regions separated by a distance of ~4 Mm.

4. MAGNETIC RESTRUCTURING

The flare is accompanied by significant restructuring of the magnetic field, which resulted in a rapid formation of a small sunspot with an intensified magnetic field from an initially diffuse magnetic field. It is worth noting that the formation of a small sunspot does not mean the appearance of a new sunspot in a quiet Sun region with a weak magnetic field. We just infer some fast redistribution or intensification of the magnetic field in the flare region from the initially diffuse background magnetic field. The spot formation happened during the short flare period <1 hr (Figure 4). Usually, the build-up of a sunspot and the intensification of its magnetic field are a relatively slow process, lasting from several hours up to several days, and unconnected to flare activity. To our knowledge, this event is the first observation of such rapid sunspot formation associated with a solar flare.

Vector magnetograms from HMI also reveal substantial changes of the magnetic field structure in the vicinity of the magnetic neutral line during the flare. In particular, the magnetic shear is sharply reduced (Figure 5). To illustrate the magnetic field reconfiguration, we calculate a nonlinear force-free field extrapolation (NLFFF) of the magnetic field using the disambiguated HMI vector magnetograms (Centeno et al. 2014) with a 720 s time cadence as the initial condition. We use the technique described in Wheatland et al. (2000), based on the minimization of functional \( \int_V | \mathbf{j} \times \mathbf{B} |^2 + | \nabla \cdot \mathbf{B} |^2 \ dV \). The results of the NLFFF extrapolation for the vector magnetograms during and after the flare are shown in Figure 5. Initially, a sheared magnetic structure elongated along the PIL (marked by red color) became less sheared after the flare. This corresponds with a transition to a more potential magnetic structure. It appears that these changes in the magnetic topology caused a rapid concentration of the magnetic field and formation of the small sunspot (Figure 4).
Previous observations showed the disappearance of small sunspot-like structures after some flares (e.g., Wang et al. 2002; Chen et al. 2007), but this event is probably the first observation of the formation of such a magnetic structure caused by a solar flare.

5. SUNQUAKE

The sunquake event was initially revealed to be a circular wave in the running difference of the Doppler velocity data. The sunquake wave (Figure 6) is best visible about 20 minutes after the initial flare impact on the photosphere located near the PIL (Figure 3). The wave front amplitude was highly anisotropic. The wave front traveling outside of the magnetic region to the southeast had the highest amplitude. In the west direction, the wave traveled toward a big sunspot and its amplitude was suppressed when it reached the sunspot.

Figure 6(b) illustrates the positions of the flare impact and the helioseismic fronts observed in the Doppler shift data, filtered for a central frequency of 6 mHz. The time–distance diagram (Kosovichev & Zharkova 1998; Zharkova & Zharkov 2007) for the helioseismic wave traveling toward the southeast is shown in Figure 6(a). The dashed curve represents the theoretical time–distance relation calculated in the ray approximation for a standard solar model. The location of this curve is chosen to approximately match the leading wave front. The short strong signal at the beginning of the event indicates the initial source motion. The parallel ridge pattern on the time distance diagram is due to the dispersion of a frequency-limited packet of the acoustic waves traveling through the solar convection layer from the flare helioseismic impact. This pattern corresponds well with previous observations of sunquakes (e.g., Kosovichev 2006, 2011b; Kosovichev & Sekii 2007; Zharkov et al. 2013).

The time–distance diagram has two interesting features. First, during approximately the first three minutes, the helioseismic source moved at a speed of about 15–17 km s\(^{-1}\) (this can be estimated from the inclined zebra-pattern on the time–distance diagram at the beginning of the flare), which is higher than the local sound speed but may correspond to the magneto-acoustic speed in the sunspot penumbra in the vicinity of the source. Second, this motion may be caused by a series of impacts due to a fast-moving magnetic reconnection process. The source motion is a common feature of sunquakes and may be essential for generating high-amplitude helioseismic waves in solar flares (Kosovichev 2014). The strongest waves are usually observed in the direction of the source motion (Kosovichev 2006).

The absence of the CME during the studied flare rules out magnetic rope eruption as a mechanism of the sunquake initiation (Zharkov et al. 2013). The possible agents generating helioseismic waves will be considered in the discussion section.

6. ELECTRIC CURRENTS IN THE FLARE REGION

In this section, we consider the evolution of the electric currents at the photosphere level. To estimate the horizontal electric currents, we use Faraday’s law applied to the 45 s LOS HMI magnetograms with the spatial resolution 1" and pixel
Figure 3. HMI images: (a) images of time derivative of the Doppler velocity, (b) images of time derivative of the HMI continuum intensity, and (c) sequence of HMI continuum intensity images. The black line shows the polarity inversion line determined from the HMI LOS magnetograms. Red and blue contours show regions of plasma upflows with the speeds: 1.79, 2.14, 2.50, 2.86, and 3.21 km s\(^{-1}\), and downflows with the speeds: 1.32, 1.58, 1.84, 2.11, and 2.39 km s\(^{-1}\) according to the HMI Doppler measurements. Dashed box points at the region where we calculated average continuum intensity are presented by the histogram in Figure 1 (the upper panel).
We can estimate the average transversal component of an electric field $E_{d} d t c L$

\[ \langle E_{d} \rangle = \frac{1}{c} \frac{d}{dt} \left( \int_{S_{c}} B \cdot dS \right) \]

We can estimate the average transversal component of an electric field $E_{d} d t c L$, where $\Phi_{z}$ is the total magnetic flux inside a contour (shown as a dashed black curve in Figure 4) with length $L$, which covers the flare region. The evolution of $d\Phi_{z}/dt$ presented in Figure 1 (histogram in bottom panel) shows that the whole flare impulse correlates with $d\Phi_{z}/dt$.

To calculate the vertical currents we use the disambiguated HMI vector magnetic field data (Centeno et al. 2014), and the Ampere’s law as in the method described in the work (Guo et al. 2013):

\[ j_{z} = \frac{c}{4\pi} (\nabla \times B)_{z} = \frac{c}{4\pi} \left( \frac{\partial B_{y}}{\partial x} - \frac{\partial B_{x}}{\partial y} \right) \]

The resulted $j_{z}$ maps, effectively averaged over 12 minutes via the HMI temporal resolution, are presented in Figure 7. We can see that the enhancement of the electric currents partially correlates with the location of the strongest photospheric impact.

To estimate the measurement error, we calculate the distribution of electric currents in a non-flaring region, and then approximate by a Gaussian. The resulting standard deviation is considered to be an error of $j_{z}$ due to noise. The time evolution of $\langle j_{z} \rangle$ averaged over the flare region (Figure 8) shows that the maximum of $\langle j_{z} \rangle$ is significantly delayed (∼30 minutes) relative to the X-ray flux observed from GOES. Perhaps the generation and dissipation of electric currents continued after the flare impulsive phase, and was associated with the magnetic restructuring. This delay may be explained by not accounting for the fine structure of the electric currents in the HMI data. The problem is we assume that the observed current density is distributed uniformly through HMI pixels, but it could be concentrated in much thinner tubes. Assuming small values of the filling factor at the flare beginning and its subsequent increase due to the current dissipation, one could fit $\langle j_{z} \rangle$ to the X-ray time profile. Resolving this issue requires high-resolution spectro-polarimetric observations.

7. RHESSI IMAGES AND SPECTRA

To determine the properties of the accelerated particles and the hot flare plasma, we use the RHESSI data in the range of 5–100 keV. RHESSI employs a Fourier technique to reconstruct X-ray emission sources Hurford et al. (2002). We applied the PIXON algorithm to synthesize the X-ray images using 1st, 3rd, 4th, 5th, and 6th detectors. In Figure 9(b), the RHESSI HXR and SXR contour images are compared with the
is the beta function, and dashed lines correspond to the sector where we calculated the time showing the location of the sunquake source, and Dopplergram image showing the locations of the sunquake front at 02:31:04 UT (marked by yellow arrows). Two dashed lines correspond to the sector where we calculated the time–distance diagram.

The current paradigm of solar flares is that the magnetic energy is released in the solar corona and transported toward the lower atmosphere by heat and energetic particles. For instance, in the hydrodynamic thick-target model (e.g., Kostiuk & Pikelnier 1975; Fisher et al. 1985; Kosovichev 1986; Allred et al. 2006; Rubio da Costa et al. 2014), high-energy electrons accelerated in the upper corona are injected along magnetic field lines into the atmosphere, generate HXR emission in the loop footpoints, and heat the upper chromosphere to high temperatures, producing a high-pressure region. The high-pressure region expands, producing upward and downward propagating shocks. The downward shock may reach the photosphere and cause a sunquake.

However, this M-class flare showed a very strong photospheric and helioseismic signal, but had relatively weak high-energy emissions and coronal dynamics. These observations suggest that a substantial part of the magnetic energy is released directly in the low atmosphere. This requires a new mechanism of energy release and transport into the low atmosphere during the flare impulsive phase. One of the possible alternative mechanisms of sunquake and flare initiation can be a rapid dissipation of electric currents or a
sharp enhancement of Lorentz force (Fisher et al. 2012; Sharykin et al. 2014). The dynamics and spatial structure of electric currents give evidence in favor of such a hypothesis. However, the relationship between the current dynamics and processes of particle acceleration is unclear. In this case, the observations show that the maximum X-ray fluxes occurred before the mean electric current reached a maximum.

The observed spatially expanding continuum emission probably is associated with the sunquake initiation. The direction of this expansion corresponds to the wave observed in the HMI LOS velocity. The estimated velocity is \(\approx 30-40 \text{ km s}^{-1}\), which is higher than photospheric magneto-acoustic speed \(\sqrt{\nu_A e^2} \sim 20 \text{ km s}^{-1}\) for a 500 G magnetic field.

Figure 7. Sequence of 12 images that shows the evolution of the vertical component of electric current density (color bar from -0.13 to 0.17 A m\(^{-2}\)). The black line shows the polarity inversion line according to the HMI LOS magnetograms; white and gray contours show upflows with speeds: 3.02, 2.65, 2.27, and 1.89 km s\(^{-1}\), and downflows with speeds: 2.10, 1.87, 1.63, 1.40, and 1.17 km s\(^{-1}\) according to the HMI Doppler measurements. Red contours show the LOS magnetic field at 1000 and 1500 G levels.
The observed upflows across the magnetic field near the PIL may play a very important role in the flare initiation process. These flows could lead to a transversal electric field \( \mathbf{v} \times \mathbf{B} \), generating circulating electric currents between the solar lower atmosphere and the corona (Figure 10). In the conditions of partially ionized magnetized plasma, ambipolar diffusion can lead to efficient dissipation of impulsive electric currents, since coefficients may be several orders higher than the coefficient of Ohmic diffusion (e.g., Khomenko & Collados 2012). To clarify such an idea, a detailed modeling of the flare plasma dynamics and heating using a multi-fluid MHD approach is needed. One of the main peculiarities of the considered flare is a fast formation of the small sunspot. The magnetic field evolution is described by the induction equation:

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \mu \Delta \mathbf{B},
\]

where \( \mu = c^2/(4\pi \sigma) \) is the magnetic diffusivity for plasma with conductivity \( \sigma \). In our case the observed sunspot formation cannot be connected with a diffusion term as it will lead only to sunspot break-up. Probably, photospheric plasma flows are the main agents of such magnetic field restructuring. Observed by HMI, the vertical upflows can contribute to the magnetic field intensification as \( \nabla \times (\mathbf{v}_0 \times \mathbf{B}_0) + \nabla \times (\mathbf{v} \times \Delta \mathbf{B}) \). However, in the case of turbulent medium \( \mathbf{v} = \mathbf{v}_0 + \delta \mathbf{v} \) and \( \mathbf{B} = \mathbf{B}_0 + \delta \mathbf{B} \) with averages \( \langle \nabla \delta \mathbf{v} \rangle = \langle \delta \mathbf{B} \rangle = 0 \), the time-averaged induction equation has the form:

\[
\frac{\partial \mathbf{B}_0}{\partial t} = \nabla \times (\mathbf{v}_0 \times \mathbf{B}_0) + \nabla \times (\nabla \times \delta \mathbf{B}_0) + \mu_{\text{turb}} \Delta \mathbf{B}_0.
\]
where $\mu_{\text{turb}}$ is the turbulent magnetic diffusivity which is larger than the classical one. Thus, we have three competing processes of magnetic field changes in the flare region: generation and transport of magnetic field by laminar (1st term) or stochastic (2nd term) flows, and magnetic diffusion (3rd term). The break-up of sunspots observed during some flares (Wang et al. 2002; Chen et al. 2007) probably connected with fast diffusion process (magnetic reconnection). In our event, the flows generating and compressing the magnetic field can be more important than diffusion, and can lead to the formation of a small sunspot from an initially diffuse sunspot region. To confirm such ideas and observations we need detailed self-consistent numerical MHD simulations.

9. CONCLUSIONS

The main results of this work are the following.

1. The SDO/HMI observations reveal significant changes of the magnetic field topology, leading to a rapid sunspot formation during the solar flare.

2. The HMI continuum emission is not located where it would be expected in the case of emission from stationary loop footpoints, but expands with velocity of ∼30–40 km s$^{-1}$.

3. The HMI Doppler shift data detect a persistent plasma upflow across the magnetic field near the PIL with a subsequent break into two upflow regions after the flare impulsive phase. Our estimates show that the upflow plays an important role in maintaining the circulating electric currents contributing to the energy release.

4. The location of the strongest photospheric disturbance leading to the sunquake does not correlate with the HXR emission source. This is not consistent with the hypothesis of the standard flare model. The sunquake generation place is located in the vicinity of the upflow break up, and partially corresponds to the most intense electric currents.

The presented analysis of HMI observations shows that the flare energy release in the low solar atmosphere is not only associated with the precipitation of high-energy particles from the corona, but is also associated with transient electric currents induced by local plasma flows. In this case the photospheric current density reached its maximum about 30 minutes after the X-ray peak, indicating that the current generation was not due to the impulsive process, but was caused by the interaction of plasma flows with magnetic fields in the low atmosphere. However, an understanding of the mechanism that causes rapid current dissipation requires high-resolution observations and theoretical modeling.

The work was partially supported by RFBR grants 13-02-91165 and 15-32-21078, President’s grant MK-3931.2013.2, NASA grant NNX14AB70G, and an NHT grant. The authors also thank the SDO and RHESSI teams for the available data and software.

REFERENCES

Allred, J. C., Hawley, S. L., Abbett, W. P., & Carlsson, M. 2006, ApJ, 644, 484
Centeno, R., Schou, J., Hayashi, K., et al. 2014, SoPh, 289, 3531
Chen, W.-Z., Liu, C., Song, H., et al. 2007, ChJAA, 7, 733
Fisher, G. H., Berclik, D. J., Welsch, B. T., & Hudson, H. S. 2012, SoPh, 277, 59
Fisher, G. H., Canfield, R. C., & McClymont, A. N. 1985, ApJ, 289, 414
Fletcher, L., Dennis, B. R., Hudson, H. S., et al. 2011, SSRv, 159, 19
Guo, Y., Démoulin, P., Schmieder, B., et al. 2013, A&A, 555, A19
Holman, G. D. 2003, ApJ, 586, 606
Hurford, G. J., Schmahl, E. J., Schwartz, R. A., et al. 2002, SoPh, 210, 61
Khomenko, E., & Collados, M. 2012, ApJ, 747, 87
Kosovichev, A. G. 1986, BCrAO, 75, 6
Kosovichev, A. G. 2006, SoPh, 238, 1
Kosovichev, A. G., & Sekii, T. 2007, ApJL, 670, L65
Kosovichev, A. G. 2011b, ApJL, 734, L15
Kosovichev, A. G. 2014, arXiv:1402.1249
Kosovichev, A. G., & Zharkova, V. V. 1995, in Proc. of the 4th Soho Workshop, Helioseismology, ed. J. T. Hoeksema, et al. (ESA SP-376; Noordwijk: ESA)
Kosovichev, A. G., & Zharkova, V. V. 1998, Natur, 393, 317
Kostiuk, N. D., & Pikelner, S. B. 1975, SvA, 18, 590
Leake, J. E., Lukin, V. S., Linton, M. G., & Meier, E. T. 2012, ApJ, 760, 109
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Lin, R. P., Dennis, B. R., Hurford, G. J., et al. 2002, SoPh, 210, 3
Rubio da Costa, F., Kleint, L., Petrovian, V., Sainz Dalda, A., & Liu, W. 2014, arXiv:1412.1815
Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, SoPh, 275, 207
Sharykin, I. N., Kosovichev, A. G., & Zimovets, I. V. 2014, arXiv:1405.5912
Sturrock, P. A. 1980, SoPh, 121, 387
Syrovatskii, S. I., & Shmeleva, O. P. 1972, SvA, 16, 273
Vainshtein, S. I., Chitre, S. M., & Olinto, A. V. 2000, PhRvE, 61, 4422
Wang, H., Ji, H., Schmahl, E. J., et al. 2002, ApJL, 580, L177
Wheatland, M. S., Sturrock, P. A., & Roumeliotis, G. 2000, ApJ, 540, 1150
Zharkov, S., Green, L. M., Matthews, S. A., & Zharkova, V. V. 2013, SoPh, 284, 315
Zharkova, V. V., & Zharkov, S. I. 2007, ApJ, 664, 573