

The Analytical Contribution to the Theory of Solar-induced Earthquakes: the Croatian December 2020 M=6.4 Case Study

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Abstract

Solar-induced earthquakes are a relatively new field of research of possible connection between events originating from Sun, and the Earth's lithosphere dynamics. This is a theory that tries to explain the temporal correlation between the solar activity increase, particularly measured using proton density values, and occurrence of the strongest earthquakes on Earth. In this paper, the case study of Croatian major earthquake in December 2020 was investigated. The increase in proton density as measured by STEREO satellite, by +4.2 standard deviations from the monthly mean value, preceded the main shock of $M=6.4$ by 16 hours. Such proton density increases, within one day before major earthquake, agrees with previous research where strong temporal correlation of those two events was found.

Introduction And Background

A sudden release of energy build-up within Earth's crust manifests itself as an earthquake. The seismic waves traveling through the ground are able to cause large destruction and loss of lives. In the last decades, science tries to develop an earthquake prediction system. However, up to current date, these efforts are still lacking of general success, with different earthquake prediction methods currently in rudimentary stages [1].

There are multiple angles of approach to this problem. Among others, there is a relatively new research that focuses on the possible causal relation between increased solar activity and the occurrence of major earthquakes on the Earth. In [2], authors reviewed latest information accumulated on the subject, stating that the effects of solar influence on the Earth's seismicity could be separated by agents of energy transfer, which could be electromagnetic emission of the Sun, particle fluxes of solar wind, solar proton events, modification of radiation belts and indirect impacts through the intermediate agent such as atmosphere disturbances and modification of atmosphere circulation as effect of solar activity.

Solar flares are eruptions of strong and localized electromagnetic radiation from surface of the Sun, driven by sudden change in magnetic field, usually from the area associated with sunspots. Powerful flares are usually accompanied by Coronal Mass Ejections (CMEs), where large amount of plasma is launched from corona into space. CMEs can sometime occur in the absence of a flare [3]. The frequency of CMEs depends on solar activity variations within solar cycles. On average, during solar maxima the Sun produces around three CMEs per day, while during solar minima one flare occurs in several days [4]. CMEs increase amount of solar wind reaching the Earth. Solar wind is a stream of charged particles, mostly protons and electrons, originating from solar surface and traveling through space [4]. The number of protons within unit of volume is termed as the solar Proton Density (PD). The general similarity of clustering of major earthquakes of $M \geq 8.0$ and the sunspot number during 20th century is demonstrated in [2]. Here, the increase in frequency of $M \geq 8.0$ earthquakes in the middle of century corresponds to the period when the Sun has been most active [5]. However, in this research author found that temporal distribution of large global earthquakes is well-described by a random process plus localized aftershocks, and apparent clustering is due to random variability. However, the conclusion is given with a limitation

because of too small length of instrumental seismological series for reliable conclusions. In [6], a dependence of earthquake counts and seismic energy released for earthquakes of $M \geq 4.5$ was researched against sunspot number data. Here, the inversed relationship is found; with decreasing the sunspot number between 1973 and 2011, the number of earthquakes increased. However, the deviation of counts from a trend is mostly positive near the minimum of solar cycles, when the flux of the galactic cosmic rays is increased. There are several papers indicating an increase in charged particles' bursts from the Sun before the major earthquake occurrences [7,8,9,10,11,12]. In [2], authors speculate that both the cosmic rays and the high energy particles precipitating from the radiation belt of inner magnetosphere in times of strong geomagnetic storms, may be a trigger of earthquakes.

In the recent results [13], 20 years of solar PD and velocity data as recorded by the SOHO mission were analyzed together with the worldwide seismicity in the corresponding period. Here, the relationship of major earthquakes and changes in density of incoming solar particles was investigated. A clear correlation between PD and occurrences of major earthquakes ($M > 5.6$) was confirmed, with increase in PD preceding occurrence of major earthquakes by approximately one day. The significance of a correlation is found to be very high, with the inaccuracy probability lower than 10^{-5} . Also, the correlation increases with the magnitude, thus the most destructive earthquakes were found to be most reliably preceded by the increased PD values. The authors propose a theoretical model that could explain the finding in terms of reverse piezoelectric effect induced by the applied electric field related to the PD. They conclude that the results open new perspectives in seismological interpretations, as well as in earthquake forecasting.

This paper contributes to the findings of relationship between major earthquakes and the increased solar activity. Here, the PD time-series before major earthquake ($M=6.4$) at the end of 2020 in Croatia were examined. The findings agree with previous work published in [13], as well as other previously mentioned researches. The increase in PD values has been found within one day before the major earthquake strike.

The Case Study

A series of earthquakes occurred in Croatia near the end of 2020. The first major shock had a magnitude of 5.2, striking the central Croatia at 05:28 UTC, December 28th 2020. The epicentre was at geographical position 45.42°N , 16.22°E near the towns of Sisak and Petrinja, and the first shock was followed by usual aftershocks. While seismologists have expected that the first shock will remain the strongest one, the much stronger strike followed on the next day in the same area. It occurred on December 29th at 11:20 UTC, with the magnitude of $M=6.4$, and with the epicentre at position 45.46°N , 16.31°E [14,15] (Figure 1). The earthquake destroyed many buildings, bringing several human casualties.

The PD dataset for December 2020 has been retrieved from NASA's public data server [16], obtained from the NASA's Solar TERrestrial RELations Observatory (STEREO) satellite [17].

Results

A series of earthquakes occurred in Croatia near the end of 2020. The first major shock had a magnitude of 5.2, striking the central Croatia at 05:28 UTC, December 28th 2020. The epicentre was at geographical position 45.42°N, 16.22°E near the towns of Sisak and Petrinja, and the first shock was followed by usual aftershocks. While seismologists have expected that the first shock will remain the strongest one, the much stronger strike followed on the next day in the same area. It occurred on December 29th at 11:20 UTC, with the magnitude of $M=6.4$, and with the epicentre at position 45.46°N, 16.31°E [14,15] (Figure 1). The earthquake destroyed many buildings, bringing several human casualties.

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The goal of the STEREO mission is to provide first-ever stereoscopic measurements to study the Sun and space weather, including CMEs. There are two STEREO satellites in the heliocentric orbit. The PD data was obtained from STEREO A satellite, referred as PLASTIC (Plasma and SupraThermal Ion and Composition) beacon data. The measurement units of PD are $1/\text{cm}^3$. Data were provided in 1-minute time resolution.

Earthquake data with occurrence time and respective magnitudes, within rectangular region bounded by coordinates 45.0°N-45.7°N and 15.8°-16.8°E, have been retrieved for the same period from the EMSC database [18]. The results are presented in Figure 2 and Figure 3, respectively.

The low proton density values were found during the majority of month, with moderate increase between 10th and 13th of December, which was followed by the decrease and finally monthly average baseline values. The major increase in PD has been recorded at December 28th, with peak value measured around 19 UTC the same day. The standard deviation of PD data within the month equals to 1.39 units, with peak value of December 28th being 7.65 units. This is an increase of 4.2 standard deviations from the mean month value (1.76). The first earthquake that hit the area occurred in the morning of December 28th, before the PD increase (Figure 2 - orange line). However, the main shock that occurred around midday of December 29th, followed the PD peak approximately 16 hours later (Figure 2 - red line). The results agree with previous findings, where the PD increase before major strikes was confirmed.

Discussion And Conclusion

The magnitude of the elaborated earthquake fits within threshold of $M>5.6$ as used in [13]. The results of PD analysis strongly agree with their findings, which strengthens positive associations found in the respective research. The first shock that happened before the PD increase does not correspond to the theory of solar-induced earthquakes. However, according [13], the second and stronger one might be the case, given that it occurred right within the temporal window of one day after the PD peak. Questions that can be discussed here are:

1. *Would the elaborated powerful $M=6.4$ shock occur at all, if the day before the PD stream was quiet or lower?*

2. *If it would occur, would it be exactly on that day, one day after PD peak or at some other time, perhaps later?*
3. *If the second earthquake would occur at December 29th, would it be that strong, if there were no PD increases on the day before, or the energy of subsequent aftershock would steadily attenuate after the first M=5.2 strike?*

In standard earthquakes, the first shocks are usually most powerful, with less-energy characterising the following aftershocks [19]. This case study series of earthquakes do not fit well into that standard model of distribution of earthquake energy in time. As the second shock has been much stronger than the first one, we speculate that its increased energy compared to the first shock might have been related to prior PD increase and that its amount of released energy might be enhanced due to solar-driven effect. It could be the case that, if the PD increase had not happened a day before, aftershocks that followed the first M=5.2 shock would not exceed that magnitude. The reason can be explained as follows. If the proton density is viewed as a strong trigger for energy release of built-up tension, it might be the case that, without its influence, the same amount of earthquake energy would still be released with time, however in series of numerous, smaller-magnitude aftershocks. Instead, with the PD peak being an energy-release trigger, the amount of seismic energy released at once might be larger.

Declarations

Author Contributions: Conceptualization, I.T.; methodology, I.T. and D.B. software, I.T.; validation, I.T., D.B. and S.K.; formal analysis, D.B. and S.K.; investigation, I.T.; writing—original draft preparation, I.T.; writing—review and editing, D.B.; visualization, I.T. and D.B.; supervision, D.B. and S.K.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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Figures

M6.4 2020/12/29 - 11:19:54 UTC Lat 45.46 Lon 16.31 Depth 10.0 km

47 km SE of Zagreb, Croatia (pop: 698,000 local time: 12:19 2020/12/29)

5 km WSW of Sisak, Croatia (pop: 35,700 local time: 12:19 2020/12/29)



Figure 1

The official position of epicenter of M=6.4 at 29th December 2020 [15] Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

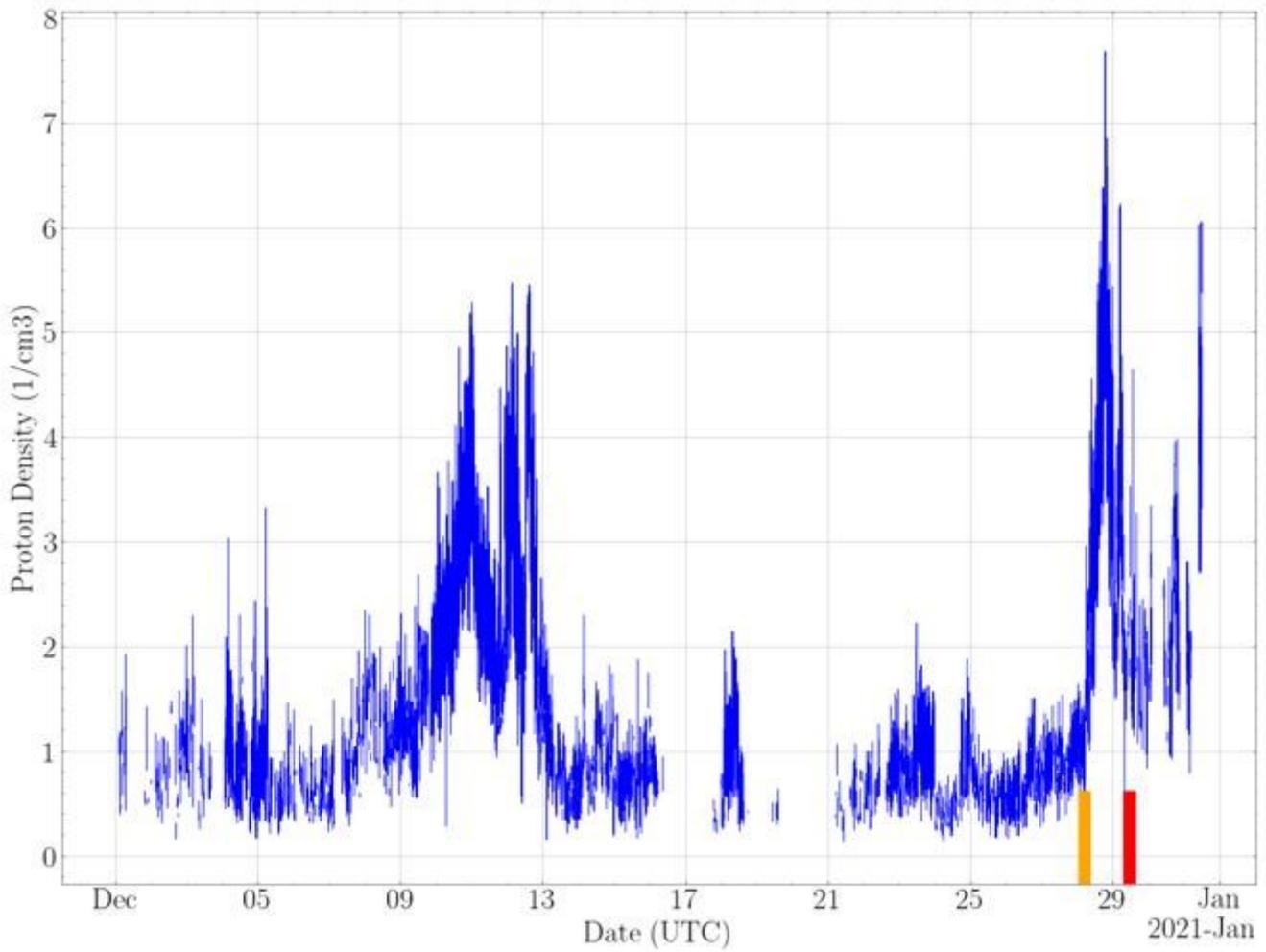


Figure 2

Proton density during December 2020, measured by STEREO A satellite. Two strongest earthquakes' times are noted with orange (M=5.2) and red (M=6.4) vertical bars at the bottom. Made by authors on the basis of [16]

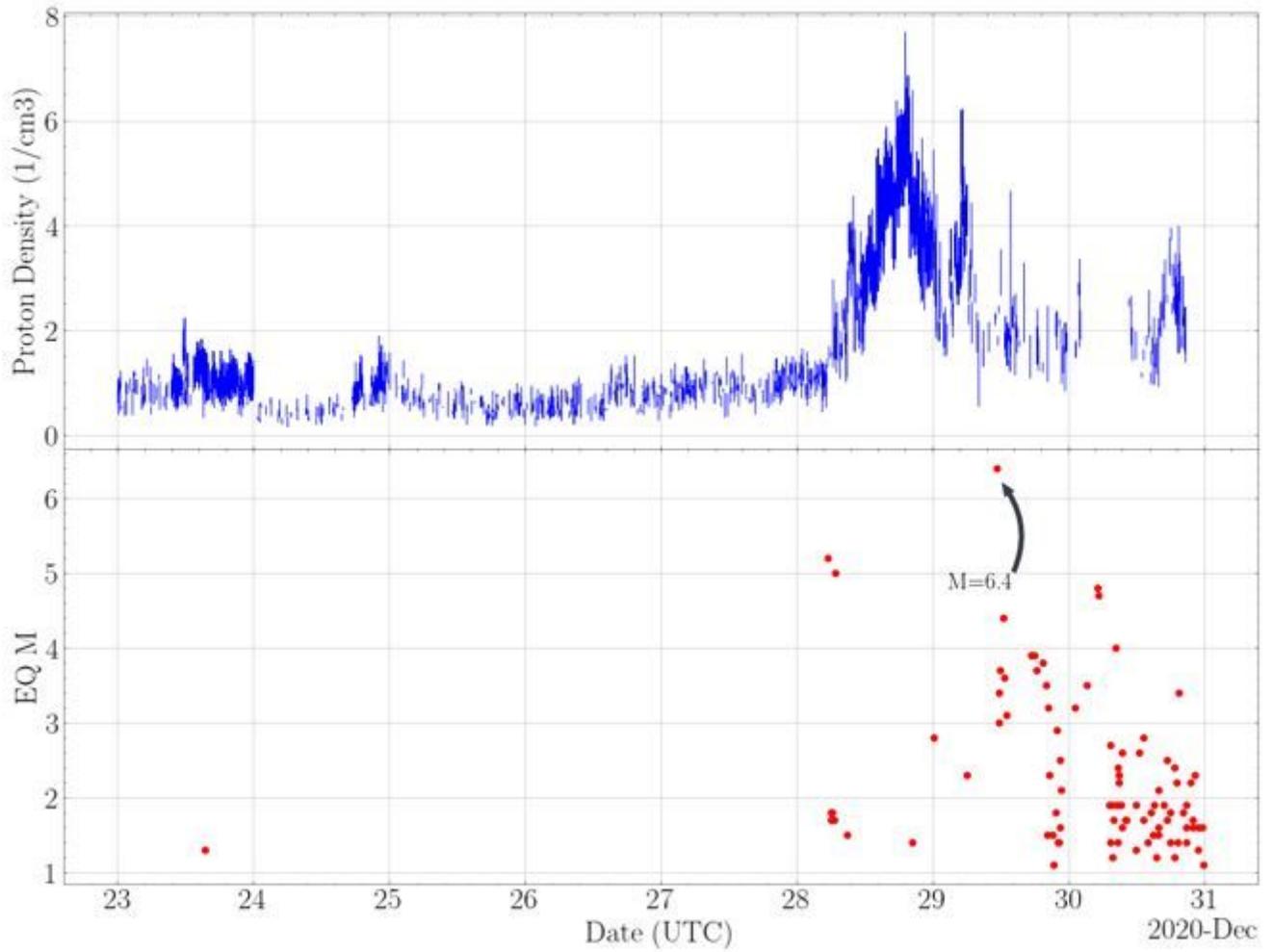


Figure 3

Proton density from December, 23rd to December 31st, measured by STEREO A satellite (upper image) and magnitudes of all recorded earthquakes by EMSC within the same period (lower image), inside the bounded area. Made by authors on the basis of [16,18]