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Investigation & Development of the «Zarshenas Earthquake Prediction Theory» (Z.E.P.T) or The Effects of Solar & Cosmic Energies on the Occurrence of Earthquakes

Pourya Zarshenas*
Faculty of Chemistry & Petroleum Sciences, Shahid Beheshti University (SBU), Tehran, Iran

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***Corresponding author:** Pourya Zarshenas, Faculty of Chemistry & Petroleum Sciences, Shahid Beheshti University (SBU), Tehran, Iran

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What is the “earthquake”?!

An earthquake (also known as a quake, tremor or temblor) is the shaking of the surface of the Earth resulting from a sudden release of energy in the Earth’s lithosphere that creates seismic waves. Earthquakes can range in intensity, from those that are so weak that they cannot be felt, to those violent enough to propel objects and people into the air, damage critical infrastructure, and wreak destruction across entire cities. The seismic activity of an area is the frequency, type, and size of earthquakes experienced over a particular time. The seismicity at a particular location on the Earth is the average rate of seismic energy release per unit volume. The word tremor is also used for non-earthquake seismic rumbling.

At the Earth’s surface, earthquakes manifest themselves by shaking and displacing or disrupting the ground. When the epicenter of a large earthquake is located offshore, the seabed may be displaced sufficiently to cause a tsunami. Earthquakes can also trigger landslides. In its most general sense, the word earthquake is used to describe any seismic event-whether natural or caused by humans-that generates seismic waves. Earthquakes are caused mostly by rupture of geological faults but also by other events such as volcanic activity, landslides, mine blasts, and nuclear tests. An earthquake’s point of initial rupture is called its hypocenter or focus. The epicenter is the point at ground level directly above the hypocenter [1-5].

Earthquake Detection

A seismogram is a record of the ground motions caused by seismic waves from an earthquake. A seismograph or seismometer is the measuring instrument that creates the seismogram. Almost all seismometers are based on the principle of inertia, that is, where a suspended mass tends to remain still when the ground moves (Figure 1).

Seismometers allow us to detect and measure earthquakes by converting vibrations due to seismic waves into electrical signals, which we can then display as seismograms on a computer screen. Seismologists study earthquakes and can use this data to determine where and how big a particular earthquake is. To record the actual motion of the ground in all three dimensions, seismologists need to use three separate sensors within the same instrument. Each sensor records the vibrations in a different direction:

- The Z component measures up/down motion.
- The E component measures east/west motion.
- The N component measures north-south motion (Figure 2)

Seismic Waves

There are two basic types of seismic wave that travel through the body of the Earth: P-waves and S-waves. P-waves are longitudinal waves that consist of a series of compressions and dilations along the direction of travel. The P stands for primary because they travel the fastest. S-waves are transverse waves, whose motion is perpendicular to the direction of travel. The S stands for shear or secondary since they are slower than P-waves [5-20].

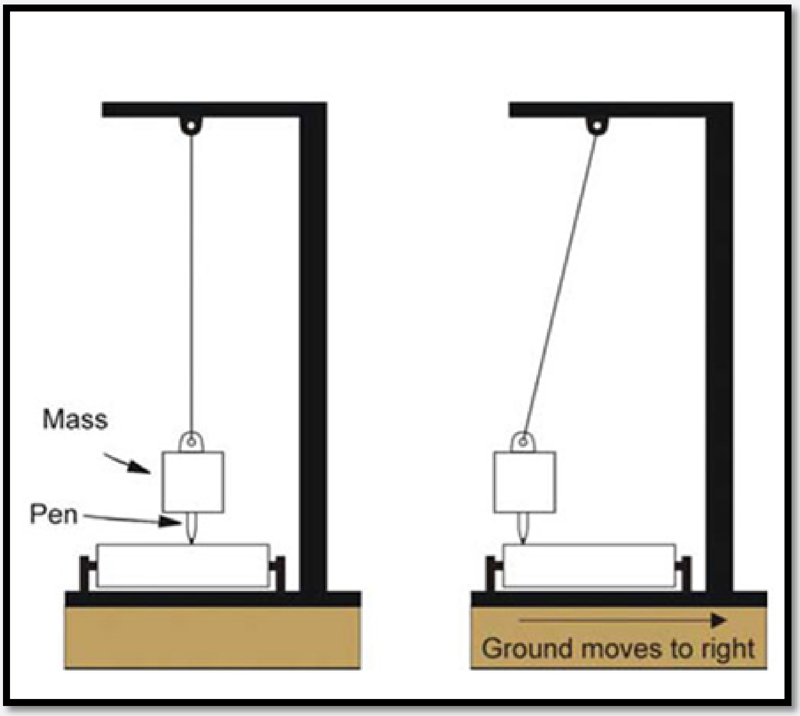

Figure 1: An illustration of a simple seismometer. The suspended mass tends to stay still, due to its inertia, when the ground moves. The pen records the relative motion. (BGS ©UKRI. All rights reserved.)

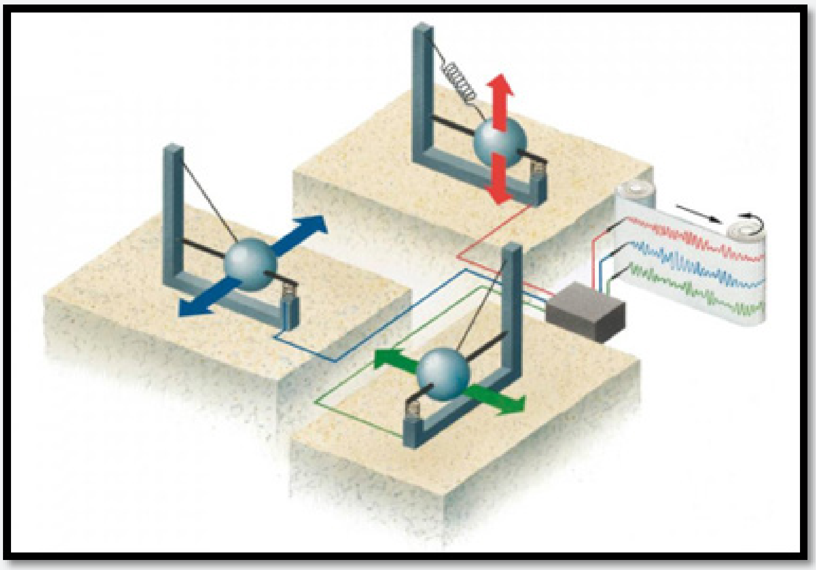

Figure 2: A three-component seismometer. Z (red) measures up/down motion; E (green) measures east/west motion; N (blue) measures north/south motion. BGS ©UKRI. All rights reserved.

Where a free surface is present (like the Earth/air interface) these two types of motion can combine to form surface waves, which produce a type of shaking that causes buildings to fail and fall down. There are two types of surface waves: Rayleigh waves and Love waves. Rayleigh waves are generated by the interaction of P- and S-waves at the surface of the Earth, while Love waves are generated by interference of multiple shear waves. The ground motions from surface waves are often much larger than those motions from body waves.

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How are Earthquakes Located?

Earthquakes generate different types of seismic waves and these travel at different speeds through the Earth. P-waves are fastest and are the first signal to arrive on a seismogram, followed by the slower S-wave, then the surface waves. The arrival times of the P- and S-waves at different seismometers are used to determine the location of the earthquake. Assuming that we know the relative speed of P- and S-waves, the time difference between the arrivals of the P- and S-waves determines the distance the earthquake is from the seismometer (Figure 3).

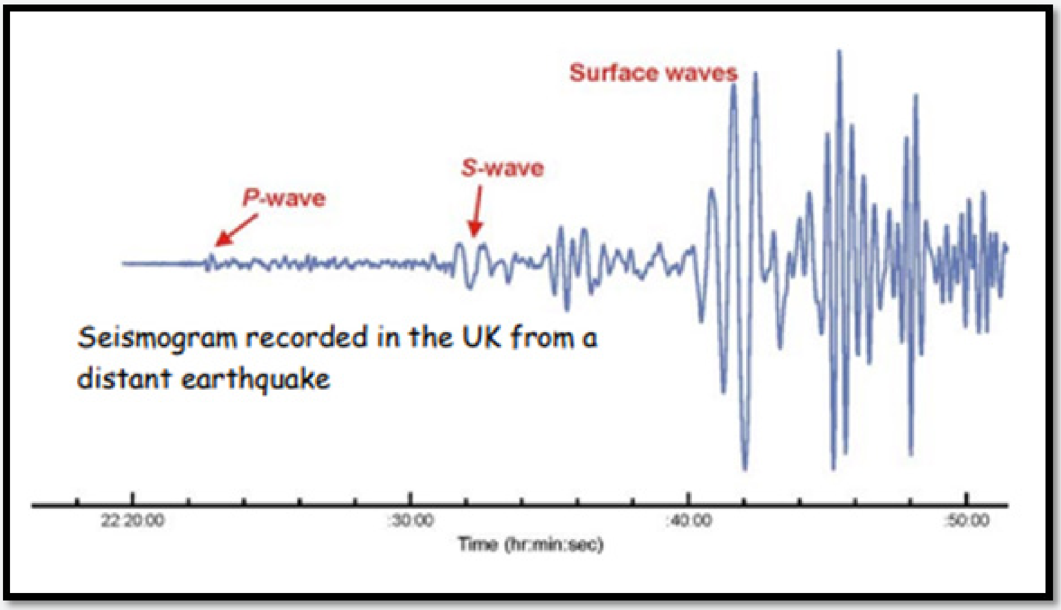

Figure 3: Seismogram showing the arrival time sequence of P-, S- and surface waves from a distant earthquake. ©UKRI. All rights reserved.

By looking at the seismograms from different recording stations, we can find out the epicentre of the earthquake. The signals arrive first at the closest station and last at the one furthest away. The time difference between the P- and S-waves tells us the distance the earthquake is from the seismometer. If we calculate the S minus P time to determine distance from the seismometer at three stations, we can work out where the epicentre of the earthquake is (Figure 4) [21-30].

How are Earthquakes Measured?

Measurement of the severity of an earthquake can be expressed in several ways, but the two most common scales used by seismologists are intensity and magnitude.

Earthquake Intensity

Intensity is a qualitative measure of the strength of shaking caused by an earthquake determined from the observed effects on people, objects and buildings. For a given earthquake, the intensity normally decreases with distance from the epicentre. There are a number of different intensity scales in use around the world that are all based on the shaking people experience and the effects it has on objects and buildings. It is also possible to estimate intensity from recordings of ground motions. In the UK, we use the European Macroseismic scale (EMS) to quantify the effect of earthquake shaking on people, objects and buildings. Estimates of intensity from different locations can be combined to make macroseismic maps that show how the strength of shaking varies (Figure 5) [31-40].

Can We Predict Earthquakes?

No. Neither the USGS nor any other scientists have ever predicted a major earthquake. We do not know how, and we do not expect to know how any time in the foreseeable future. USGS scientists can only calculate the probability that a significant earthquake will occur in a specific area within a certain number of years.

An earthquake prediction must define 3 elements:

1) the date and time,
2) the location,
3) the magnitude.

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Yes, some people say they can predict earthquakes, but here are the reasons why their statements are false:

1. They are not based on scientific evidence, and earthquakes are part of a scientific process. For example, earthquakes have nothing to do with clouds, bodily aches and pains, or slugs.

2. They do not define all three of the elements required for a prediction.

3. Their predictions are so general that there will always be an earthquake that fits, such as,

(a) There will be a M4 earthquake somewhere in the U.S. in the next 30 days.

(b) There will be a M2 earthquake on the west coast of the U.S. today.

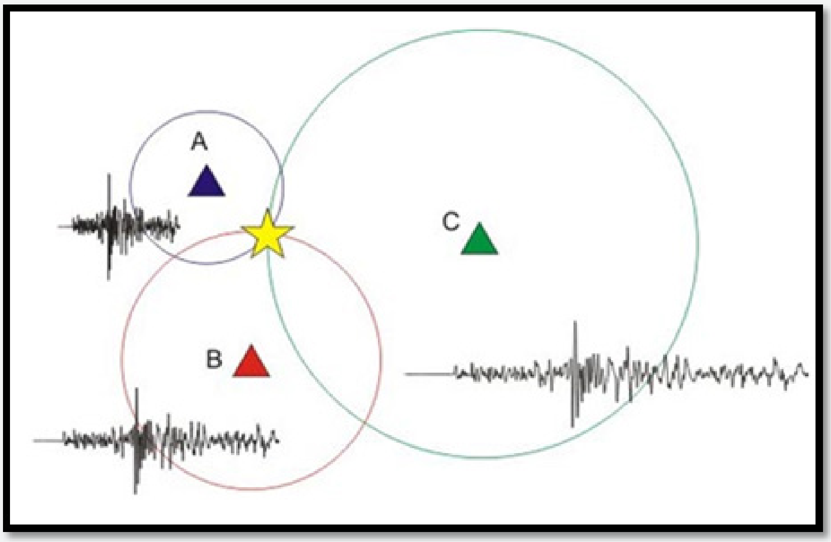

Figure 4: Imagine A, B and C are three different seismometer stations at distant locations. Once we know the distance to an earthquake from three seismic stations, we can determine the location of the earthquake. Draw a circle around each station with a radius equal to its distance from the earthquake. The earthquake occurred at the point where all three circles intersect. BGS ©UKRI. All rights reserved.

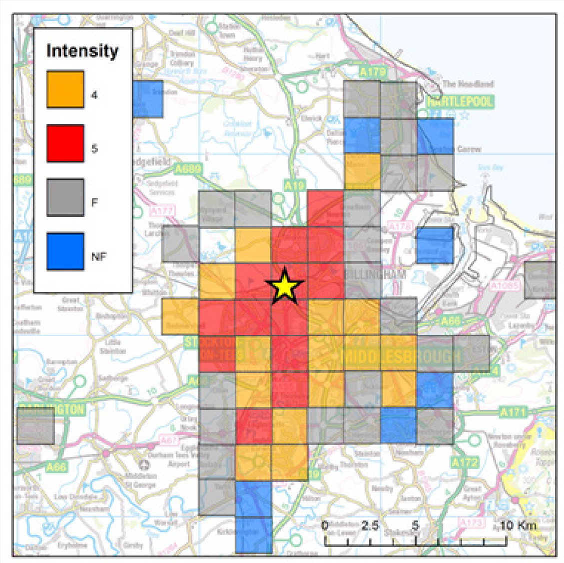

Figure 5: Macroseismic intensities (EMS) for the magnitude 3.1 ML earthquake on 23 January 2020, near Stockton-on-Tees, UK. The yellow star shows the earthquake epicentre. Intensities are calculated in 2 km grid squares from over 840 reports from people who felt the earthquake. A minimum of five observations are needed in any grid square to calculate a value of intensity, otherwise the value is recorded as 'Felt', but no intensity is calculated (shown by grey squares). Blue squares indicate that reports from these locations suggest that the earthquake was not felt. BGS © UKRI. All rights reserved.

If an earthquake happens to occur that remotely fits their prediction, they claim success even though one or more of their predicted elements is wildly different from what actually occurred, so it is therefore a failed prediction. Predictions (by non-scientists) usually start swirling around social media when something happens that is thought to be a precursor to an earthquake in the near future. The so-called precursor is often a swarm of small earthquakes, increasing amounts of radon in local water, unusual behavior of animals, increasing size of magnitudes in moderate size events, or a moderate-magnitude event rare enough to suggest that it might be a foreshock. Unfortunately, most such precursors frequently occur without being followed by an earthquake, so a real prediction is not possible. Instead, if there is a scientific basis, a forecast might be made in probabilistic terms.

An earthquake forecast was made in China several decades ago based on small earthquakes and unusual animal activity. Many people chose to sleep outside of their homes and thus were spared when the main earthquake indeed occurred and caused widespread destruction. However, this type of seismic activity is rarely followed by a large earthquake and, unfortunately, most earthquakes have no precursory events whatsoever. The next large earthquake in China had no precursors and thousands of people died. The USGS focuses its efforts on the long-term mitigation of earthquake hazards and by helping to improve the safety of structures, rather than by trying to accomplish short-term predictions [41-50].

Nobody Can Predict Earthquakes, but We Can Forecast them

After devastating earthquakes, it's common to see discussion of earthquake prediction. An earthquake prediction requires, in advance, the specific time, location and magnitude of a future quake. However, earthquake prediction has never been achieved successfully in a way which could be repeated. Often, "predictions" are vague, such as describing the future earthquake as happening "sooner or later", and the underlying methods are not scientifically founded. That's not to say we don't know anything about what earthquakes will happen in the future. While earthquake scientists are not able to predict earthquakes, we are able to forecast them.

What is an Earthquake Probability and How is it Calculated?

Earthquake probabilities describe the chances of an earthquake of a certain magnitude occurring within a region over a span of years. Probabilities can be calculated based on the average rate of past seismic activity in a region. This technique is particularly useful in regions where earthquakes have been recorded by seismographs, which first came into wide use in the early 1900s. Scientists can obtain additional, though less precise, information by digging trenches to examine the geological record for earthquake ruptures that occurred in ancient history. Probabilities also can be derived mathematically. For example, seismologists estimate the number of years it could take to experience an earthquake of a certain magnitude by accounting for two processes:

1. the buildup of strain onto faults as a result of the continual motion of tectonic plates, and

2. the relieving of strain as a result of fault slip, which can occur as an earthquake or as slow creep along a fault line without an earthquake.

What is an Earthquake Forecast?

Earthquake forecasts provide information on the likelihood of earthquakes over a shorter time window of time. Forecasts are used typically to describe aftershocks, which tend to follow a pattern of decreasing frequency and magnitude over time after an earthquake.

What's the Difference Between a Prediction and a Forecast?

A forecast tells you the chance or the probability of a range of future earthquakes in a given region. This includes how big the quakes may be (their magnitude), and how frequently they will occur over a specified time period [51-60].

Earthquake forecasts are built on observations of past earthquake activity, which may stretch back decades, centuries or even thousands of years. These observations are analyzed and modelled, and we use our understanding of the physics of earthquake occurrence to determine the chances of future seismic activity.

When looking at catalogues of the time, location and magnitude of past earthquakes, it becomes very clear that damaging earthquakes are more likely to strike along the boundaries of the tectonic plates that make up Earth's crust than in the interior of those plates. In recent decades, the installation of worldwide networks of seismic recorders has also allowed the detection of much smaller quakes and tremors - including events too small to be perceived by people. This data have revealed important relationships between the relative numbers of small and large earthquakes which underpin earthquake forecasting. Earthquake forecasts can be made for the short term (weeks, months, years) and the long term (decades to centuries).

How Little Quakes Give Us Clues About Big Ones

One of the fundamental discoveries of seismology is the fact that, in a given region, there will be on average about ten times as many magnitude 2.0 earthquakes as magnitude 3.0 quakes. There will also be ten times as many magnitude 3.0 as magnitude 4.0, and so on. This relation allows us to use small earthquakes, which happen often, to forecast less frequent, large earthquakes - which may not yet exist in historical records.

Observations and analysis of major earthquakes from around the world over the past century or more has also helped us to

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understand their aftershocks. These shocks diminish over time in a statistically characteristic way.

This relationship is used for short-term forecasts of active earthquake sequences, to estimate the magnitude and frequency of earthquakes in the weeks, months and years following the main quake. In these forecasts, large magnitude aftershocks are always possible, and in some cases, they can be larger than the mainshock. Such forecasts have been used in many countries around the world. After the magnitude 7.1 earthquake at Ridgecrest, California, in 2019, a series of forecasts were released, and updated as new data was received. Currently, there is a 10% chance of one aftershock of magnitude 5.0 to magnitude 5.9 in the Ridgecrest region in the next year. Knowing what to expect during an active sequence is important for planning how to respond and recover from a strong earthquake.

Records in Rock

Geological investigations extend the record of major earthquakes beyond those captured in earthquake catalogues. These studies look for evidence of ground-rupturing earthquakes along a particular fault. Take the Alpine Fault, a 600 km section of the boundary of the Pacific and Australian plates in Aotearoa New Zealand. Analysis of rocks along the fault has provided strong evidence that, over the past 8,000 years or so, one ground-rupturing earthquake of around magnitude 8.0 has occurred roughly every 300 years. The most recent major rupture on the Alpine Fault was in 1717, more than 300 years ago.

Using this data, earthquake scientists have estimated that there is a high probability - a 75% chance - of rupture on this fault in the next 50 years. There is an approximately 80% chance that this earthquake will be a magnitude 8.0 or above. This type of medium- to long-term forecast allows for preparedness such as planning for emergency response. In the case of the Alpine Fault, the AF8 program was put in place to keep the community informed and engaged, and to plan the response and build resilience for the expected future earthquake [61-70].

Maps and Codes

Our best long-term forecasts use data from earthquake catalogues and geological studies, combined with earthquake behavior patterns and other knowledge such as geodetic models - which use GPS networks to tell us how Earth's surface is under strain and moving as tectonic plates shift. These forecasts typically provide not just the magnitude and location, but also the range of the intensity of ground-shaking from future earthquakes. Much like climate forecasts, these forecasts combine multiple models into a single forecast. This is used to map regions of low to high probability of experiencing damaging earthquakes. These long-term forecasts inform building codes around the world and guide the design and construction of buildings and infrastructure to withstand strong ground shaking from future earthquakes and, ultimately, to save lives.

My Inspiration

My inspiration in formulating this theory is the great Muslim scientist and astronomer al-Biruni. Abu Rayhan Muhammad ibn Ahmad al-Biruni (973 - after 1050) known as al-Biruni, was a Khwarazmian Iranian scholar and polymath during the Islamic Golden Age. He has been called variously the "founder of Indology", "Father of Comparative Religion", "Father of modern geodesy", and the first anthropologist. Al-Biruni was well versed in physics, mathematics, astronomy, and natural sciences, and also distinguished himself as a historian, chronologist, and linguist. He studied almost all the sciences of his day and was rewarded abundantly for his tireless research in many fields of knowledge.

Royalty and other powerful elements in society funded al-Biruni's research and sought him out with specific projects in mind. Influential in his own right, Al-Biruni was himself influenced by the scholars of other nations, such as the Greeks, from whom he took inspiration when he turned to the study of philosophy. A gifted linguist, he was conversant in Khwarezmian, Persian, Arabic, Sanskrit, and also knew Greek, Hebrew, and Syriac. He spent much of his life in Ghazni, then capital of the Ghaznavids, in modern-day central-eastern Afghanistan. In 1017, he travelled to the Indian subcontinent and wrote a treatise on Indian culture entitled Tārīkh al-Hind ("The History of India"), after exploring the Hindu faith practiced in India.

He was, for his time, an admirably impartial writer on the customs and creeds of various nations, his scholarly objectivity earning him the title al-Ustadh ("The Master") in recognition of his remarkable description of early 11th-century India. There is also a famous story about her journey with Ibn Sina , a great Muslim sage and physician, which is as follows: One day, al-Biruni and Avicenna went out of the city where he lived to observe the stars and stopped in the desert next to a mill until it was sunset and a little after night when the miller came out and addressed al-Biruni and Avicenna and said that he wanted to go to the mill and lock its doors and if they want to spend the night in the mill, come: Because my ears can't hear and it's raining tonight, you'll get wet, and no matter how much you knock on the door in the middle of the night, I won't hear it, and you have to stay under the rain all night!.

Suddenly, Avicenna interrupted the miller's words and said: What are you saying, man?! This man who is sitting here is the greatest scientist and mathematician as well as an astronomer in the world and according to his estimation it will not rain tonight! The miller said, anyway, I said my word. Meanwhile, my ears can't hear and if you knock on the door at night, I won't understand! After midnight, it started to rain heavily, and no matter how much al-Biruni and Avicenna knocked on the door of the mill, the miller did not wake up until morning and the miller came out and saw that both of them were shivering from the cold. They both asked the miller: How did you know it was going to rain last night? The miller replied, I didn't know, my dog knew! Avicenna said: How

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does a dog know that rain is coming? The miller said: Every night when it is going to rain, the dog comes inside the mill so that it does not get wet. Al-Biruni suddenly shouted and said, “God! I know so much that I know as much as a dog, but I still don’t know”.

Powering Earthquake Monitors with Solar

Earthquake monitoring systems are crucial for predicting and tracking earthquakes. These systems collect data on earthquakes, such as the seismic activity’s magnitude, location, and duration. In the past, earthquake monitoring systems were powered by electricity from the grid, but this is no longer the case.

Using solar to generate the power needed to monitor earthquakes in previously unreachable places provides critical information that can save lives and reduce damage. One example of how solar panels are being used for earthquake monitoring is in this recent installation in Haida Gwaii, off the British Columbian coast.

Here, natural resources Canada uses a network of solar panels powered by seismographic stations. The data collected by these stations are used to study earthquakes and to develop early warning systems.

Not only does using solar allow systems to be installed in critical locations, but solar panels are also environmentally friendly and do not emit harmful gases or pollutants. They are also more cost-effective, requiring minimal maintenance and can last for several decades. Solar panels are changing how many industries operate, and earthquake monitoring systems are a prime example of the flexibility of the uses for mobile power.

Powerful Eruptions on the Sun Might Trigger Earthquakes

Through decades of research, scientists have learned that large, powerful earthquakes commonly occur in groups, not in random patterns. But exactly why has so far remained a mystery. Now, new research, published July 13 in Scientific Reports, asserts the first strong- though still disputed- evidence that powerful eruptions on the Sun can trigger mass earthquake events on Earth. “Large earthquakes all around the world are not evenly distributed… there is some correlation among them,” says Giuseppe De Natale, research director at the National Institute of Geophysics and Volcanology in Rome and co-author of the new study. “We have tested the hypothesis that solar activity can influence the worldwide [occurrence of earthquakes].”

A Solar Origin for Earthquakes

To the unaided eye, the Sun might seem relatively docile. But our star is constantly bombarding the solar system with vast amounts of energy and particles in the form of solar wind. Sometimes, however, formidable eruptions on the Sun’s surface cause coronal mass ejections, or especially energetic floods of particles - including ions and electrons - that careen through the solar system at breakneck speeds. When they reach Earth, these charged particles can interfere with satellites, and under extreme circumstances, take down power grids. New research suggests that particles from powerful eruptions like this -specifically, the positively charged ions - might be responsible for triggering groups of strong earthquakes.

Earthquakes typically occur when rocks grind past one another as Earth’s tectonic plates shift and jostle for position. When the intense friction that’s locking plates together is overcome, the rocks break, releasing tremendous amounts of energy and shaking the ground. But scientists have also noticed a pattern in some large earthquakes around the planet: they tend to occur in groups, not at random. This suggests there may be some global phenomenon that’s triggering these worldwide earthquake parties. And though many researchers have done statistical studies to try to determine a cause before, no compelling theories have yet been rigorously proven [71-80].

So, to tackle the lingering mystery, the researchers of this latest study combed through 20 years of data on both earthquakes and solar activity, searching for any possible correlations. Specifically, the team used data from NASA-ESA’s Solar and Heliospheric Observatory (SOHO) satellite, compiling measurements of protons (positively charged particles) that come from the Sun and wash over our planet. This is not the first-time scientists have tried to link solar activity to earthquakes, however. In 1853, a Swiss astronomer named Rudolf Wolf tried to connect sunspots - locations of intense magnetic activity on the surface of the Sun- to earthquakes. More recent experiments have also sought such a link, but strong statistical evidence remains out of reach.

A 2013 paper published in Geophysical Review Letters, for instance, looked at 100 years of sunspot and geomagnetic data, finding no evidence of a connection between the Sun and earthquakes. Partly because long-term efforts to find a link between the Sun and earthquakes have come up short, this latest claim that solar protons may play a role has been met by notable skepticism in the research community. Some are wary of the statistical analysis performed on the data, while others take issue with how the data was selected. “The results [from the new paper] alone don’t tell you there’s actually any real physical connection, I think,” says Jeremy Thomas, a research scientist at Northwest Research Associates who was not involved in the new research. “There could be, but I don’t think it’s proving that.”

As is almost always the case with science, more research is required before we can know for sure if the Sun can trigger earthquakes. But if future work manages to cement the proposed connection, keeping a close eye on our shining star might help us better predict and prepare for when the ground unexpectedly and violently shakes beneath our feet, possibly helping save lives. Due to the many human and financial losses by powerful earthquakes, many efforts have been made to predict the principal parameters of earthquakes based on precursor behaviors. Based on historical

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seismic data, a number of scientific reports and papers have indicated that there is a noticeable relationship between solar-terrestrial interactions and earthquake occurrence. Wolf (1853), as a great astronomer, claimed that sunspots could influence the occurrence of earthquakes.

Many papers have analyzed different time scales of global seismicity data and the results of some of them are contradictory. Odintsov et al. (2006) reported that the number of earthquakes is highest during solar-cycle sunspot maximum, but Simpson (1967) and Huzaimy and Yumoto (2011) declared that the seismicity is highest in the declining phase and minimum of the solar cycle. From the opposite results of these works, we can presume that probably the difference came from the different cyclicities of the global seismicity. Love and Thomas (2013) did not find consistent and statistically significant distributional differences between the earthquake-number distributions and below and above the median of the solar-terrestrial averages.

They also considered time lags between the solar-terrestrial variables and the number of earthquakes, but again no statistically significant distributional difference was found. They did not reject the null hypothesis of no solar-terrestrial triggering of earthquakes. In the next section, we recall the main results in favor of a correlation, mentioning some explanation of the possible coupling. Then, we present three case studies where the correlation seems apparent when the geomagnetic activity in the form of the Dst index in a short time scale of 100 days was considered. Then four different time series data, including earthquake catalog data and the daily average of F10.7, Kp, and ap indices, were analyzed during a long interval in time, including two solar cycles, i.e., from 1 January 2000 to 28 April 2022. Regarding global seismicity, this study focuses on $M \geq 7.0$ earthquakes. Finally, we compared the results obtained with those found when the correlation is made with a series of temporally randomized earthquake catalogs.

Some Previous Main Results in Favor of a Possible Correlation

In the ionosphere, the solar wind produces electrical currents. Then, on the Earth's surface, these electrical currents cause magnetic field fluctuations. These fluctuations, penetrating the Earth's interior, induce the electrical currents J and, in the presence of the Earth's magnetic field B, generate electromagnetic force, known as Lorentz force $F = J \times B$. To study the relation between earthquakes and the Lorentz force, acting at the near onset times of strong earthquakes, Urata et al. (2018) examined the Kp index, a logarithmic measure of the magnetic field deviation. The time-varying Kp index gives J, which in turn determines F. The Lorentz force tilts the subtle force balance in the Earth's crust towards triggering the release of stress-strain energy, initiating an earthquake in a similar way as a mountain climber's step can trigger avalanches. The internal dynamics, however, are highly statistical.

Urata et al. (2018) investigated variations of the Kp index for 28 days before and after three major seismic events of $M \geq 6$ in 2016 and 2017. They statistically analyzed the Kp index for the times of earthquakes between 1932-2016. Stacking of thousands of Kp data shows an effect of the geomagnetic field on earthquake triggering. They found a distinct pattern of the Kp fluctuations prior to earthquakes, indicating the synchronization of geomagnetic surges and seismicity. These synchronizations are quite complex, reflecting the regional characteristics and the earthquake magnitude itself. M8 class earthquakes are associated with the Kp surge more than M6 class ones.

The geomagnetic disturbance, typically the magnetic storm, is one of the major factors which synchronize with earthquakes. Tarasov (2021) has shown that bursts of the intensity of ionizing electromagnetic radiation from the Sun, as well as geomagnetic storms, cause a statistically significant decrease in the total number of earthquakes on Earth. After bursts of ionizing radiation from the Sun, a statistically significant decrease in the total energy of earthquakes occurs, and after geomagnetic storms, its increase is observed. This is mainly due to an increase in the number of the strongest earthquakes with $MS > 7$ after geomagnetic storms and a decrease in the number of such earthquakes after bursts of ionizing electromagnetic radiation from the Sun.

During geomagnetic storms and for several days after them, the probability of occurrence of strong earthquakes increases more than two times, and after bursts of ionizing electromagnetic radiation from the Sun, this probability decreases almost twice. Guglielmi et al. (2021) declared that the correlation between earthquakes and magnetic storms exists objectively. The problem deserves further study using statistical hypothesis testing methods and special attention should be paid to distinguish between causal and acausal correlations clearly. Sobolev (2021) compared the times of occurrence of earthquakes with magnitudes $M \geq 6.5$ all over the world with the commencement times of the strongest magnetic storms with the planetary Kp index above 7.

In the interval from 1994 to 2017, 17 earthquakes occurred within two days after 50 storms which correspond to their non-random occurrence with a probability above 95%. However, the recent paper of Marchitelli et al. (2020) reproposed an external origin of the triggering of earthquakes again. In their paper, Marchitelli et al. analyzed 20 years of proton density and velocity data, as recorded by the SOHO satellite, and the worldwide seismicity in the corresponding period, as reported by the ISC-GEM catalog. They reported a clear correlation between proton density and the occurrence of large earthquakes ($M > 5.6$), with a time shift of one day.

If we accept that there is a connection between the occurrence of large earthquakes and solar-terrestrial activities, therefore, there must be a coupling between the Sun, ionosphere, and lithosphere. Gribbin (1971) declared that this coupling could cause small changes in the Earth's rotation rate and then result in seismic events. Moreover, solar- geomagnetic activities might induce eddy electric currents in rocks along faults which results

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in heating them and reducing their shear resistance, or induced currents that might cause a piezoelectric increase in fault stress. In such cases, an earthquake is likely to occur because, in the critical-point accumulation of stress along a fault, a small nudge might trigger an earthquake.

What is to establish is whether this contribution is significant or not, i.e., if the occurrence of earthquakes is strongly or weakly affected by the solar conditions. In the latter case, the correlation would be within casual fluctuations. In other terms, we formulate a null H0 hypothesis, i.e., there is a cause-effect correlation between geomagnetic sun-induced activity and earthquakes, and an alternative Ha hypothesis that affirms that there is no correlation or that any apparent correlation is only due to chance. After a series of analyses also involving the simulation of 100 random earthquake catalogs, we rejected the null hypothesis in favor of the alternative casual Ha hypothesis.

On the Correlation Between Solar Activity and Large Earthquakes Worldwide

Large earthquakes occurring worldwide have long been recognized to be non-Poisson distributed, so involving some large-scale correlation mechanism, which could be internal or external to the Earth. Till now, no statistically significant correlation of global seismicity with one of the possible mechanisms has been demonstrated yet. In this paper, we analyze 20 years of proton density and velocity data, as recorded by the SOHO satellite, and the worldwide seismicity in the corresponding period, as reported by the ISC-GEM catalogue. We found clear correlation between proton density and the occurrence of large earthquakes ($M > 5.6$), with a time shift of one day. The significance of such correlation is very high, with the probability to be wrong lower than 10-5.

The correlation increases with the magnitude threshold of the seismic catalogue. A tentative model explaining such a correlation is also proposed, in terms of the reverse piezoelectric effect induced by the applied electric field related to the proton density. This result opens new perspectives in seismological interpretations, as well as in earthquake forecasts. Worldwide seismicity does not follow a Poisson distribution, not even locally. Many authors have proposed specific statistical distributions to describe such a non-poissonian behavior but none of these is really satisfactory, probably because the underlying physical process has not been really understood. Many authors have hypothesized that a tidal component may show up in earthquake activity, but generalized evidence has never been proven. Quite recently, some authors suggested that earthquake occurrences might be linked to earth rotation speed variations.

There is also a smaller number of researchers that studied possible links among solar activity, electro-magnetic storms and earthquakes. The first idea that sunspots could influence earthquake occurrence dates back 1853 and is due to the great solar astronomer Wolf. Since then, a number of scientists have reported some kind of relationship between solar activity and earthquake occurrence; or among global seismicity and geomagnetic variation or magnetic storms. Also, some mechanisms have been proposed to justify such correlations: small changes induced by Sun-Earth coupling in the Earth's rotation speed; eddy electric currents induced in faults, heating them and reducing shear strength; or piezoelectric increase in fault stress caused by induced currents.

However, none of these studies allowed achieving a statistically significant conclusion about the likelihood of such mechanisms. On the contrary, argued that there is no convincing argument, statistically grounded, demonstrating solar-terrestrial interaction favoring earthquake occurrence. However, the large interest nowadays for possible interactions between earthquake occurrence and extra-terrestrial (mainly solar) activity, is testified for instance by the Project CSES-LIMADOU, a Chinese-Italian cooperation aimed to launch a satellite to study from space the possible influence of solar activity and ionospheric modifications on the seismicity. In this paper, we will definitively establish the existence of a correlation between solar activity and global seismicity, using a long data set and rigorous statistical analysis. Once such a correlation is demonstrated, we propose a tentative, at the moment qualitative, mechanism of possible sun-earthquakes interaction.

Statistical Assessment of the Correlation Solar Activity-Earthquakes

Since our aim was to verify the existence of a link between solar activity and earthquakes, we considered two data sets: worldwide earthquakes, and SOHO satellite proton measurements. As far as earthquakes are concerned, we used the ISC-GEM catalogue. We chose it since, at the moment, this is the only worldwide data set with homogeneous magnitude estimates that allows for sound statistical analysis. We selected this catalog since it is the only complete one, with homogeneous magnitudes, albeit only from $M = 5.6$. It in fact includes all the Global CMT solutions and adds about 10% of events that are missed by the latter. In these cases magnitudes are expressed as mb and Ms proxies. We checked its completeness for $M \geq 5.6$ since 1996. The earthquake catalogue currently (ver. 7.0) goes up to the end of 2016.

The SOHO (Solar and Heliospheric Observatory) satellite is located at the L1 Lagrange point at about 1.5 million of kilometers from the Earth. Hourly data in terms of proton density ρ and velocity v are available for about 85% of the time since early 1996. Combining the two variables in the catalogue, we could infer, as further variables, the proton flux ρv, and the dynamic pressure $\rho v2/2$. We have therefore considered, in our analyses, four different proton variables V: flux, dynamic pressure, velocity, and density. We computed the average of each proton variable in consecutive daily intervals. As a first step, each one of these variables V has been compared with the worldwide seismic events with $M \geq 5.6$ in the period 1996/01/21-2016/12/31, considering

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the daily number of events only. The choice of this data set is due to the fact that it is the largest one.

The daily number of events is more significant than the daily total moment, since we are interested in the number of individual rupture processes, rather than in a quantity that spans several orders of magnitude. Moreover, for large numbers of events, over a few thousands, the Gutenberg Richter relation is universally valid and, since earthquakes are self-similar, the number of events equivalently reflects the size of the main shock. We also chose not to decluster the event data set for two reasons. First, according to, it is wrong to distinguish between main events, aftershocks, and background activity; second, declustering is somewhat arbitrary but would anyway result in a completely uncorrelated catalogue, likely destroying key information we are looking for [81-89].

Proton density and velocity vary with time, so if any correlation with earthquakes does exist, it must be found either in terms of different earthquake rates according to high/low proton values, or before/after the high or low values (Figure 6). This shows, with an example made on 15 days of catalogue, the overall procedure and illustrates the meaning of the used conditions for the statistical tests. The figure shows an example of application of the statistical method to 15 days of the catalogue. The istogram levels give the daily value of the proton density; the red line shows the level of the current density threshold (all values of it are consecutively tested).

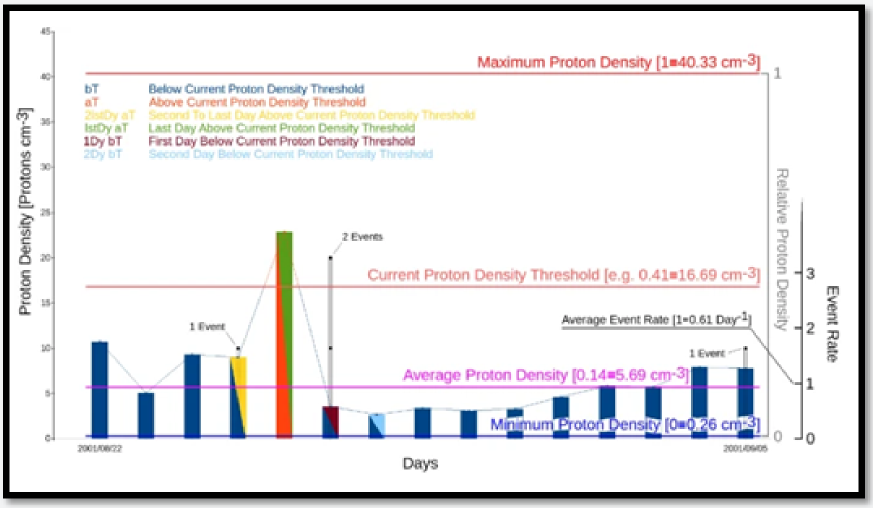

Figure 6: This shows, with an example made on 15 days of catalogue, the overall procedure and illustrates the meaning of the used conditions for the statistical tests.

The black points indicate the occurrence of earthquakes in that day. The istogram colours indicate the conditions which are applied for the statistical tests; in particular, violet indicates the first day below the current proton density threshold (i.e. the first day after a value above the threshold), the green indicates the last day above the density threshold, and so on (as indicated in the legend). High values of earthquake frequency in one of these particular periods indicate the tendency of earthquakes to occur before, during, after (and with what time lag) a period of proton density above the current threshold. Also shown in the figure are the minimum (blue), average (purple) and maximum (intense red) values of proton density for the whole catalogue used.

Another important remark is that since we consider 4 variables, 5 conditions and, later in the discussion, 6 magnitude thresholds with different temporal windows, we choose to use non-dimensional algorithms, to facilitate comparison. The first step consists in computing the average of V (Vav). Because of the necessity of working with non-dimensional variables, we express the non-dimensional average of V (Vav_ad) as Vav-ad=(Vav-Vmin)/(Vmax-Vmin) approximated to the second significant digit. Then, we define a varying threshold, as VT=Vmin+Vstep(Vmax-Vmin) for each variable V, where Vstep ranges from the average value of Vav_ad to 1, with steps of 0.01. For a given condition C, and for each VT, we can count the number DC of days that satisfies the condition and the corresponding number of events EC occurring in those days. D and E are respectively the number of days where SOHO data are available and the total number of events that occur in those days. In this way for each VT, we can simply define an event relative rate R=(EC/DC)/[(E-EC)/(D-DC)].

In below Figure we show the event relative rate R versus Vstep, for each condition C, represented for the 4 variables: flux, dynamic pressure, velocity, and density. This approach implies that, if earthquakes occur casually with respect to proton variables V, the event relative rate R should oscillate around 1, within a random uncertainty (Figure 7). For most of the CV pairs shown in this, we stopped computation at Vstep ≈ 0.4. This is due to the fact that, for larger threshold values, DC/D becomes smaller than 0.015, thus giving a too poor sampling. This value has been selected so to have at least about 100 days satisfying the selected condition. The final step consists in evaluating if R is significantly different from 1, for any of the variables V, in any of the conditions C within a VT range.

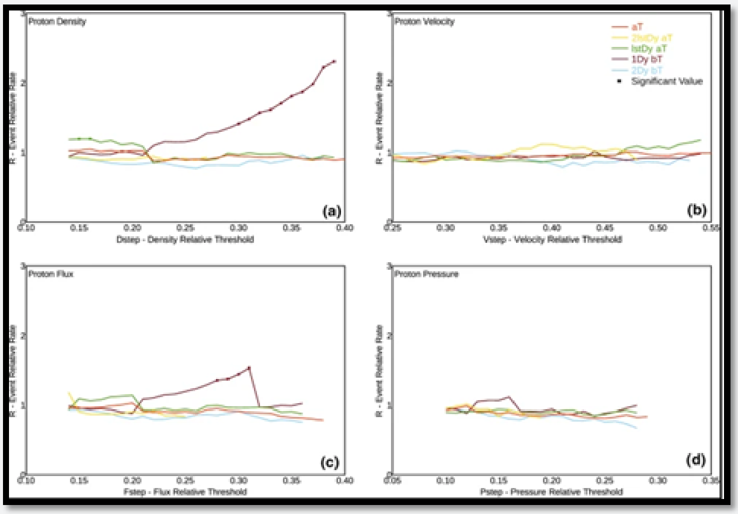

Figure 7: Plots of the Event Relative Rate as a function of the non-dimensional Density Threshold, for:

(a) proton flux;

(b) proton dynamic pressure;

(c) proton velocity;

(d) proton density.

This means we need to devise a test starting from the assumption that earthquake occurrence is not poissonian. We choose to create 105 synthetic data sets, using the real data inter-event time intervals randomly combined. This empirical approach ensures us a synthetic catalog that has exactly the same statistical properties as the actual one, since we obtain a random data set with the same survival function as the real one. The survival function gives the probability of occurrence of inter-event time intervals and is commonly used to describe the statistical properties of earthquake occurrence. We followed this empirical approach because, as stated above, there is no satisfactory distribution that describes inter-event time intervals in a non declustered event series.

To clarify our approach, in the below we compare the real event survival function with a Poissonian one with identical event rate. As it is clear, the inter-arrival times of the real catalogue are markedly different from a Poisson distribution (Figure 8). We wanted therefore to test whenever any random distribution could casually yield the same effects, in terms of R values, as the real one. Only if, for a given VT, R is higher than any of the values Rrand obtained by randomly distributed time intervals distributions, we consider that value as significant, thus clearly indicating correlation. This bootstrap technique corresponds to perform a statistical test with the null hypothesis that the observed correlation is only casual; given the number of 105 realizations considered, we can reject the null hypothesis, for the significant cases in which no value of R is greater or equal to the observed one, with a probability to be wrong lower than 0.00001. In Fig.2 we show the statistically significant values of R, as formerly defined, as squares.

We want to highlight this criterion is extremely rigorous (confidence level is very high, 99.999%, with respect to the normally used levels of 95-99%), but in fact our aim is to demonstrate, beyond any reasonable doubt, if correlation between any proton variables and earthquakes does exist. For the same reason we used all the available proton data, even when a single day was preceded and followed by data lacking: this obviously led to R value, and hence significance, underestimation. The analyses so far described, depicted in (Figure 2), show that the condition 1Dy bT in Table 2 (i.e. one day after the variable decrease below the threshold value) is the only significant one, and only for ρ (density) and ρv (flux) variables. Moreover it monotonically increases as the threshold value increases, at least up to values of threshold not too high, where the sampling becomes too poor.

Such an increasing trend of the R peak value is best observed for the density ρ, but it can be observed also, although with lower peak values, for the flux ρv. We can therefore state that the

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most striking correlation between proton variables and global seismicity is with earthquakes occurring during the 1st day after the density value ρ decreases below a certain threshold, in the Vstep range of 0.31-0.39. Such a range for Vstep corresponds to a range of proton density between 12.7 and 15.9 counts cm-2. As a final step, we have further checked the dependence of the observed R peak values on the magnitude threshold of the earthquake catalogue. We have then progressively increased the lower magnitude threshold of the used seismic catalogue. Below figure clearly shows the correlation peak that becomes larger and larger with increasing magnitude cut-off. These results confirm the existence of a strongly significant correlation between worldwide earthquakes and the proton density in the near the magnetosphere, due to solar activity (Figure 9).

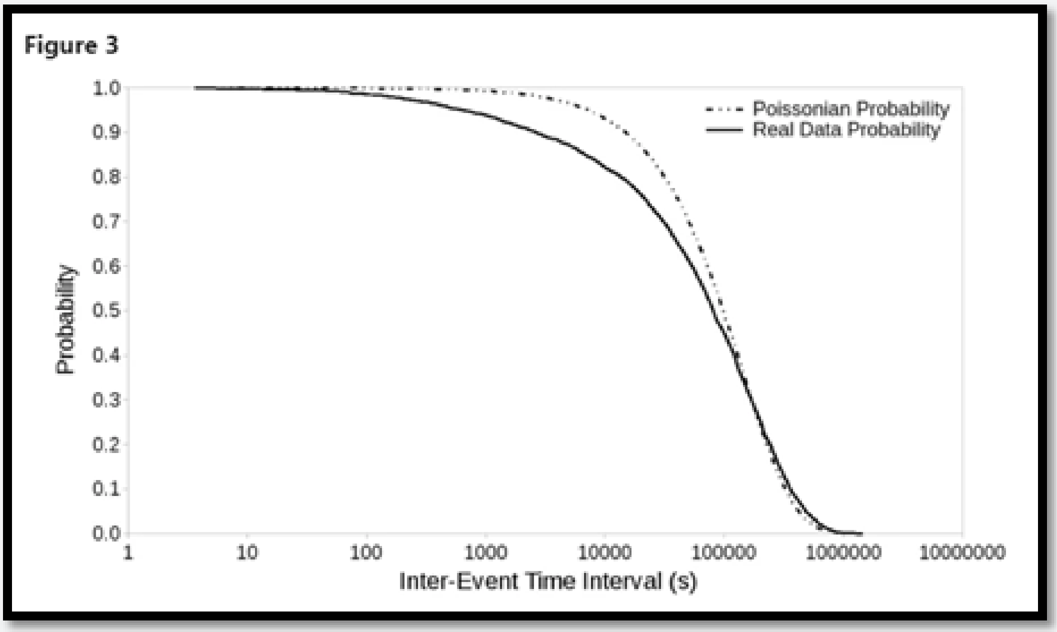

Figure 8: Inter-arrival time distribution of the events in the seismic catalogue (solid line). The dotted line shows, for comparison, the expected distribution of inter-arrival times for a Poisson distribution with the same event rate.

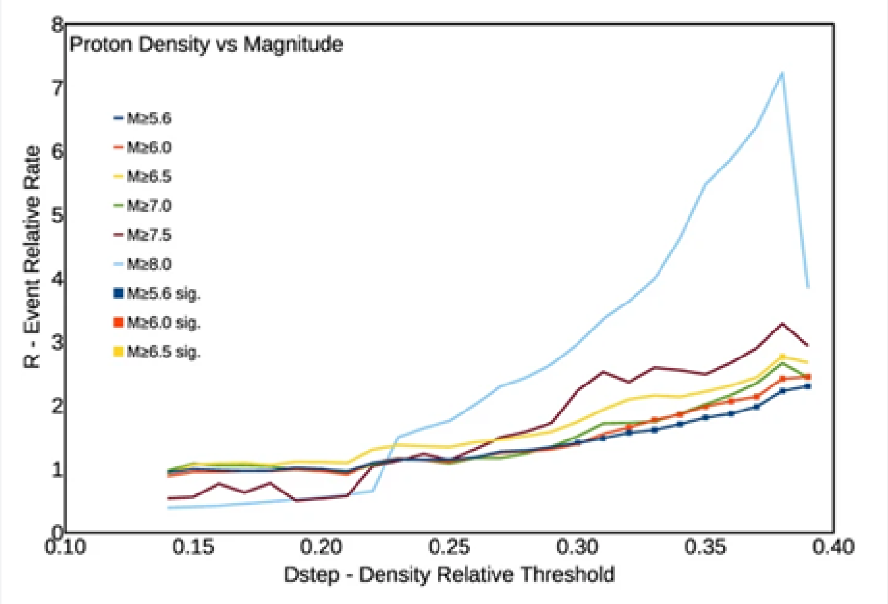

Figure 9: Plots of the Event Relative Rate R as a function of the normalized proton density, and for the condition 1Dy bT (earthquakes occurring within 24 h from the value of density decreasing below the threshold value). Colours indicate different lower cut-off magnitudes in the catalogue.

Testing and Discussion of Statistical Results

A further way to check the robustness of the inferred correlation is to divide the catalogue in two parts, using the first half (1996-2005) to infer the best correlation parameters, and then applying the inferred parameters to the second half (2006-2016) to see if it continues to indicate a significant correlation. This is a classical test to verify that the inferred correlation is not just a result of overfitting the data.

The first part of the catalogue is the 'learning' set, whereas the second part is the 'testing' set. If the results obtained with the testing set, using the optimal criteria inferred from the learning one, also indicate a significant correlation, then such a correlation is robust and not just an overfitting of data. We then divided the catalogue in two parts, each one 10 years long as previously indicated, and inferred the best model from the first part. We actually inferred, as the best model (of highest R score) from the first half of the catalogue, the day after the proton density peak decreases below the threshold; then, we computed the R score obtained, with the same model, from the second half of the catalogue.

We have then generalized this test, in order to check also the relative performance of the different catalogues containing, respectively, the shallow (Depth < 60 km) and the deep (Depth > 60 km) earthquakes. This further subdivision is also interesting, for two reasons: firstly, the mechanism of deep events could be in principle somewhat different from the crustal ones; secondly (and somewhat related), because they are generally not followed by sustained aftershock sequences. The catalogue of deep events is then a naturally 'declustered' one, and so it can help to understand how the proton density-earthquake correlation would work for a declusterd catalogue. Obviously, the process of artificial declustering is a highly subjective one, and could then destroy the main features of the catalogue linked to the correlation. As it is evident, all the curves, for all the sub-catalogues, show a marked increase of the R score as a function of the proton density threshold used.

This makes clear that the effect of increasing seismicity with increasing proton density always occurs. The significance level to accept the observed correlation, computed the same way explained for (Figure 2) (i.e. randomly generating many catalogues sharing the same interevent distribution than the real one) goes from 0.001 of the learning catalogue and catalogue of deep events, to 0.00001 of the whole catalogue, catalogue of shallow events and testing catalogue. We should hence conclude, from this test, that the observed correlation is always significant, that it does not represent an overfitting of data (because the same parameters inferred from the learning catalogue also well describe the testing one), and that also the catalogue of only deep events shows a correlation with proton density.

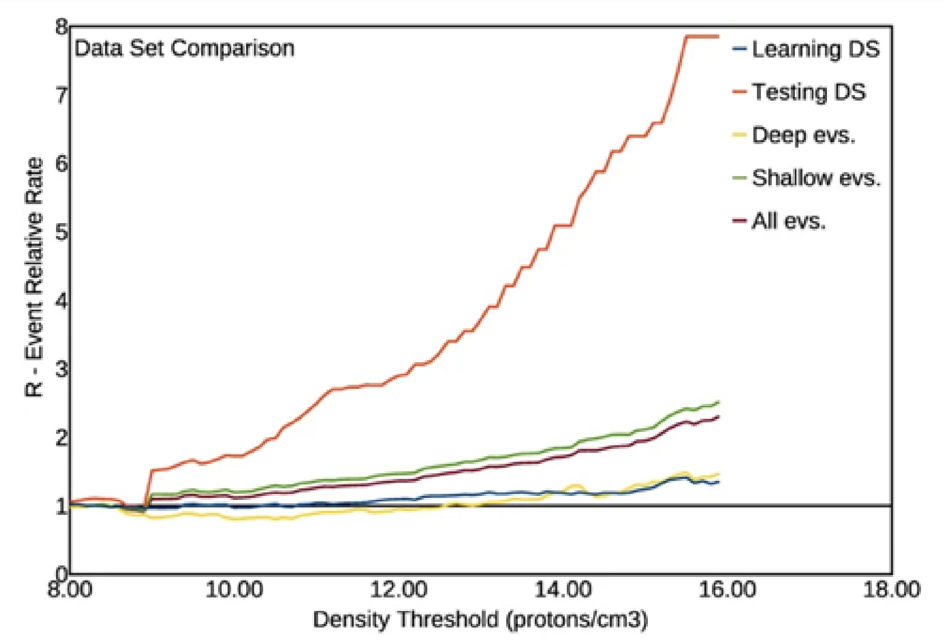

Figure 10: Plots of the Event Relative Rate R as a function of the absolute value of proton density, and for the condition 1Dy bT (earthquakes occurring within 24 h from the value of density decreasing below the threshold value). Colours indicate different subdivisions of the catalogue (the results for the total catalogue are shown by the brown curve).

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We should also note, however, that the solar activity (proton density) in the second part of the catalogue is significantly lower than in the first part; and such a decrease is particularly marked in the last period (2013-2016) where, for any given density threshold, there are less density peaks and consequently less periods of 24 h following the density peaks (Figure 10). It can be even more interesting to see what happens by subdividing the catalogue in smaller parts, and to study the goodness of the inferred model obtained for different subdivisions, progressively larger, of the catalogue. The procedure here used as a test for the inferred correlation has been adapted from the concept of the Molchan diagram. We started considering a time window whose length in days is 0.01 of the total catalogue: 0.01 × 6,774 = 67.74, rounded to 68 days.

We than consider all the parts of length 68 days in the catalogue, by sliding progressively the 68 days windows of 1 day each step, until the 68th day corresponds to the ending day of the catalogue. In this way, we obtain 6,774 - 68 = 6,706 time windows. For each time window, we compute if the Event Relative Rate R, for events occurring within 24 h from the end of a density peak, is higher or lower than the average number of events per day computed from the whole catalogue (0.95 events/day): if it is higher, the prediction outcome is positive, otherwise it is negative. In case there is, in a given time window, no day occurring after the end of a density peak, that window is excluded from the count. On the Y axis, we indicated the fraction of the sliding time windows with a prediction failure.

Then, we repeat the same procedure and computation for time windows progressively larger, from a fraction 0.01 to 1 of the total catalogue time duration; for each fractional length of the sliding window, indicated on the X axis, we report on the Y axis the fraction of prediction failures. It is obvious that, for a totally random outcome, the fraction of prediction failures is around 0.5; a number significantly smaller indicates a significant correlation, whereas a number significantly higher would indicate a significant anti-correlation. We have applied this procedure to all the sub-catalogues here considered (learning catalogue, testing catalogue, shallow event catalogue, deep event catalogue) as well as to the whole catalogue. Figure shows the results of such analysis, for the best fitting density threshold, computed for the total catalogue, of 15.5 protons/cm^3.

The results synthesized in Figure are effective to give a complete, clear picture of the robustness of the results, and then of the inferred correlation. In fact, they clearly show values of the failure fraction, for the learning catalogue, the testing catalogue and the total catalogue, which are significantly smaller than 0.5, except for very low time windows. The integral below the respective curves here represent the total failure fraction: it varies from a minimum of 0.05 for the learning catalogue and the whole catalogue, to a maximum of 0.21 for the catalogue of deep earthquakes. It is also worthy of note that some catalogues show even better results with slightly different density thresholds.

The catalogue of deep earthquakes, for instance, has a total failure fraction of only 0.14 for a density threshold slightly higher: 16.1 protons/cm^3; the ‘testing’ catalogue has a better minimum of total failure fraction of 0.14 for a lower density threshold: 13.3 protons/cm3. So, all the obtained values of global failure fraction are considerably smaller than 0.5, thus confirming the predictivity of the method, and then the significance of the correlation. We should note that the method we use here conceptually differs from the Molchan diagram also for the shape of the space involved to discriminate purely randomly results from a significant correlation. In fact, a purely random result is represented as the diagonal of a square with surface normalized to 1.0 in the Molchan diagram; in our method, conversely, a purely random result is represented by a horizontal line with a constant value Y = 0.5.

In both diagrams, the surface (integral) below a curve representing purely random results has a value around 0.5; significantly lower values indicate, on the contrary, significant degree of predictivity (Figure 11). All the obtained results and tests point out the correlation between earthquakes and proton density is highly statistically significant, even if for catalogues with too large earthquake magnitude thresholds it does not strictly pass the significance test. This is due to the fact that the three higher magnitude data sets (M ≥ 7.0, 7.5, 8.0) are composed by a really small number of event and furthermore, for such reason, the Gutenberg-Richter relation is no longer valid. As a final test, we wanted to check if the proton density catalogue is completely uncorrelated.

We know, as stated above, that the seismic catalogue of strong earthquakes is non-Poissonian and internally correlated, so we have analyzed the proton density series to check if it were characterized by a white noise spectrum that would indicate an uncorrelated process. We simply computed the power spectrum, which is shown in picture; it is clearly very different from a white spectrum, presenting at least two sharp peaks. We performed such a computation on the longest uninterrupted time window that has a 405 days length. This evidence testifies that neither the proton density distribution is random. So, this definitively confirms that the observed correlation between the seismic catalogue and the proton density cannot be likely obtained by chance; because the likelihood that two quantities, each of them internally correlated, show a clear mutual correlation only by chance is negligible (Figure 12).

In conclusion, the analysis of the 1996-2016 worldwide earthquake catalogue shows a significant correlation with the measured proton density in the same period. Such correlation is described by a larger probability for earthquakes to occur during time windows 24 h long just after a peak period (meant as a period spent over a certain threshold) in proton density due to solar activity. This kind of correlation between worldwide seismicity and solar activity has been checked also with other variables linked to solar activity, including proton velocity, dynamical pressure of protons, proton flux, and proton density. However, a significant correlation can be only observed with proton flux, besides proton density.

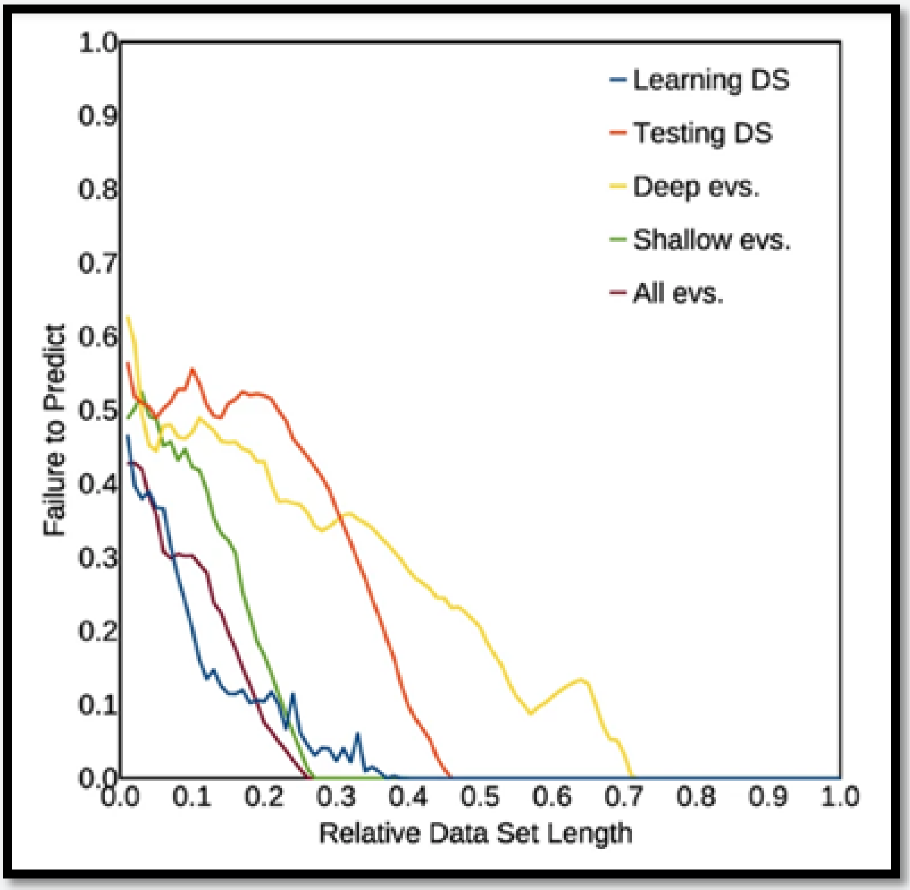

Figure 11: Diagrams showing the fraction of failure to predict as a function of the length of sliding time windows in which the catalogue is subdivided. The length is shown, on the X axis, normalized to the total length of the catalogue. Curves for different catalogues are shown with different colors (see also the text). The results shown here have been computed using the value for the proton density threshold ρT = 15.5 protons/cm3, which represents the optimal value, which minimizes the integral below the curve for the total catalogue. The value of the integral below each curve represents the total prediction failure fraction; it should be close to 0.5 for a random, non-predictive model. The values found here are: 0.05 for the total catalogue; 0.05 for the 'learning' catalogue; 0.08 for the shallow events catalogue; 0.17 for the 'testing' catalogue; 0.21 for the deep events catalogue.

The correlation is anyway much sharper using simple proton density, so evidencing that this is the really influent variable to determine correlation with earthquake occurrence. This correlation is shown to be statistically highly significant. The high significance of the observed correlation is also strengthened by the observation that, increasing the threshold magnitude of the earthquake catalogue, the correlation peak becomes progressively larger. The application of a further appropriate methodology of testing, using concepts similar to the Molchan diagram, also confirms the statistical significance of the observed correlation. The correlation between large earthquakes worldwide and proton density modulated by solar activity then appears to be strongly evident and significant.

A possible Qualitative Model to Explain Observations

Once a strong correlation between proton density, generated by solar wind, and large earthquakes worldwide has been assessed, the next step is to verify if a physical mechanism exists which could explain such a result. Several mechanisms have been proposed, till now, for solar-terrestrial triggering of earthquakes. Although former observations about solar-terrestrial triggering were not convincing, some of the formerly proposed mechanisms

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could explain our results, which are on the contrary statistically significant. In particular, Sobolev and Demin studied the piezoelectric effects in rocks generated by large electric currents.

Our observed correlation implies that a high electric potential sometimes occurs between the ionosphere, charged by the high proton density generated at higher distances, and the Earth. Such a high potential could generate, both in a direct way or determining, by electrical induction, alterations of the normal underground potential, an electrical discharge, channeled at depth by large faults, which represent preferential, highly conductive channels. Such electrical current, passing through the fault, would generate, by reverse piezoelectric effect, a strain/stress pulse, which, added to the fault loading and changing the total Coulomb stress, could destabilize the fault favoring its rupture.

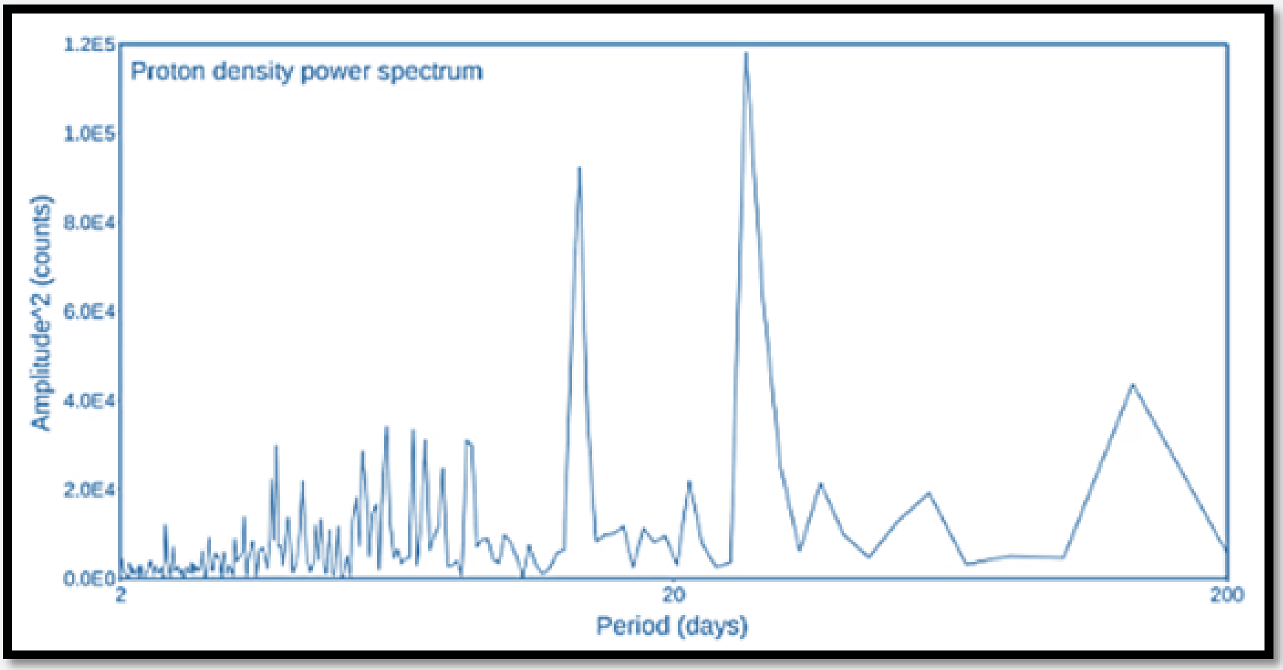

Figure 12: Power spectrum computed for the proton density catalogue. The spectrum is computed only for the maximum consecutive period of data with no interruption, lasting 200 days.

The reverse piezoelectric effect would be due, in rocks, by the quartz minerals abundant in them. Such effect can work, in principle, for all kinds of faults. The piezoelectric effect, in fact, acts to produce a pulse of dilatation or contraction on a particular axis of the crystal, depending on the polarity of the electrical current. For quartz crystals randomly distributed on a fault surface of any orientation, the net effect is a pulse of strain/stress normal to the fault, because the other strain/stress components compensate among them into the bulk rocks. The normal stress can stabilize or destabilize any kind of fault, depending on the sign; however, since it is a transient pulse, it has an effect only in case it is able to instantaneously increase the total Coulomb stress on a given fault above the fracture strength, thus generating the earthquake. It would then represent only a small destabilizing effect over an already critically loaded fault.

So, the earthquake cycle would be anyway dominated by tectonic phenomena, but this small external triggering effect could generate the observed slight correlation among worldwide earthquakes. These kinds of effects, induced by high electrical potential between the ionosphere and the Earth, should likely be accompanied by electrical discharges in atmosphere, which would cause luminescence phenomena. Actually, there are numerous observations of macroscopic luminescence phenomena (named Earthquake Lights) before and accompanying large earthquakes. Moreover, these phenomena could also cause strong electromagnetic effects, which would be recorded as radio-waves; even such phenomena have been largely reported as accompanying, and generally preceding, large earthquakes.

More in general, a lot of electro-magnetic anomalies, often well evident, are more and more frequently reported associated to moderate to large earthquakes. The recent scientific literature is full of hypotheses about how such electromagnetic effects, associated to large earthquakes, and could be generated. The most debated question is if they can be considered as precursors

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(or maybe triggers) for large events, or they are caused by the process of slip on the faults which also generate the earthquake. Here we suggest that the increase in the proton density near the magnetosphere can qualitatively explain all these observations, and also give a physical basis to our statistical observations.

Conclusions

This paper gives the first, strongly statistically significant, evidence for a high correlation between large worldwide earthquakes and the proton density near the magnetosphere, due to the solar wind. This result is extremely important for seismological research and for possible future implications on earthquake forecast. In fact, although the non-poissonian character, and hence the correlation among large scale, worldwide earthquakes were known since several decades, this could be in principle explained by several mechanisms.

In this paper, we demonstrate that it can likely be due to the effect of solar wind, modulating the proton density and hence the electrical potential between the ionosphere and the Earth. Although a quantitative analysis of a particular, specific model for our observations is beyond the scope of this paper, we believe that a possible, likely physical mechanism explaining our statistical observations, is the stress/strain pulse caused by reverse piezoelectric effects. Such pulses would be generated by large electrical discharges channeled in the large faults, due to their high conductivity because of fractured and water saturated fault gauge.

The widespread observations of several macroscopic electro-magnetic effects before, or however associated to large earthquakes, support our qualitative model to explain the observed, highly statistically significant, proton density-earthquakes correlation. It is important to note that our hypothesis only implies that the proton density would act as a further, small trigger to cause the fracture on already critically charged faults, thus producing the observed large scale earthquake correlation. Such a small perturbation would add to the main factor producing worldwide seismicity, which is tectonic stress.

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