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Solar induced earthquakes – review and new results

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Abstract. A lot of information has been accumulated recently demonstrating impacts of solar activity on the Earth's seismicity. We observe the transition from correlation-driven papers to the more physical based works. The effects of solar influence 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. Effects of the galactic cosmic rays should be taken into account including the Forbush decreases, which are result of geomagnetic storms. MHD electromagnetic sounding stimulating the earthquake activity could be considered as a physical model of the geomagnetic storms effect on the seismic activity. The most intriguing effects discovered recently is the inducing the strong M>7 earthquakes by the precipitation from additional radiation belt at L-shell 1.5-1.8 formed after the strong geomagnetic storm. Precipitation of relativistic particles from this shell induces the strong earthquakes with delay nearly 2 months. One very importing agent of geosphere coupling including the energy transfer into the lithosphere is the Global Electric Circuite. It is difficult to explain the observed phenomena by simple transformation of solar energy into mechanical deformation, it seems that more plausible explanation is the pumping of energy into the Earth's crust volume being in a metastable state.

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- Time clustering of M≥8.0 earthquakes and solar activity variations.
- Variations of solar activity and correlation with earthquakes with M≥4.5.
- Paleo-earthquakes at Northern Tian-Shan and solar activity.
- Flows of high-energy charged particles associated with earthquakes.
- New results on correspondence between dynamics of radiation belt and seismic activity.
- Conclusion.
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Time clustering of M≥8.0 earthquakes and solar activity variations

Fig.1 shows temporal distribution of earthquakes with M≥8.0 that occurred since 1900 [*Michael,2011a*], where ovals 1-3 mark the periods of their clustering - at the beginning of XX century, in the middle, and at the beginning of XXI century. This result was debated at the meeting of SSA in 2011, where the question was: whether the observed clustering has some physical cause [*Michael,2011b; Bufe and Perkins,2011*]. In conclusion, it was noted by [*Michael,2011a*]: "...even if there is a global process leading to the generation and clustering of earthquakes, the length of the instrumental seismological series is currently too small to reliably make conclusion. This situation may change either (1) - with the accumulation of seismological data in the future, or (2) - with the advent of the physically justified hypothesis of earthquake generation, which will positively affect the test results."

As regards a paragraph (2), it may be interesting to pay attention on a new hypothesis of earthquake generation (triggering) by the flux of high energy charged particles which intensity may vary with solar activity changes. For example, **Fig.2** shows yearly sunspot numbers since 1900 (http://www.sidc.be/silso/datafiles), which demonstrates long term variations: solar grand minima (ovals 1, 3) and solar grand maximum (oval 2) [*Usoskin et al, 2007*]. Comparison of **Fig.1** and **Fig.2** allows one to suggest that strong earthquake clustering occurs in both the grand solar minima (ovals 1 and 2) when the flux of Galactic cosmic rays is expected to be increased, and the grand solar maximum as well (oval 2), when the flux of Solar cosmic rays is expected to be increased.

As regards paragraph (1), dealing with the length of seismological series, one may increase it either using the series of smaller magnitude earthquakes, or using data on strong paleo-earthquakes (*next slides*).

Fig.1

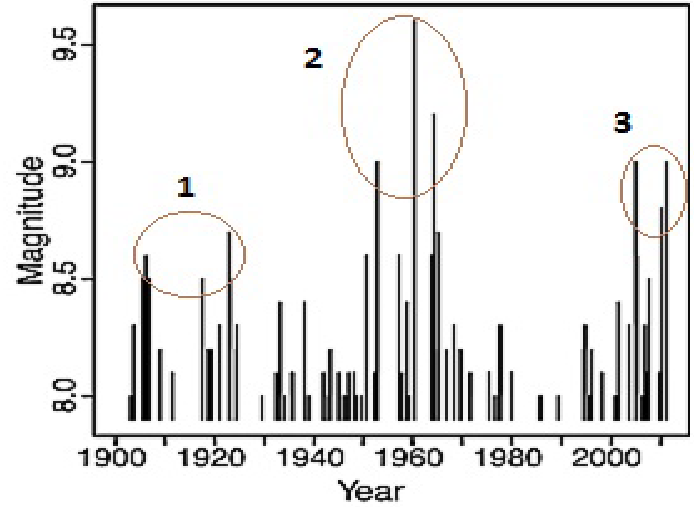
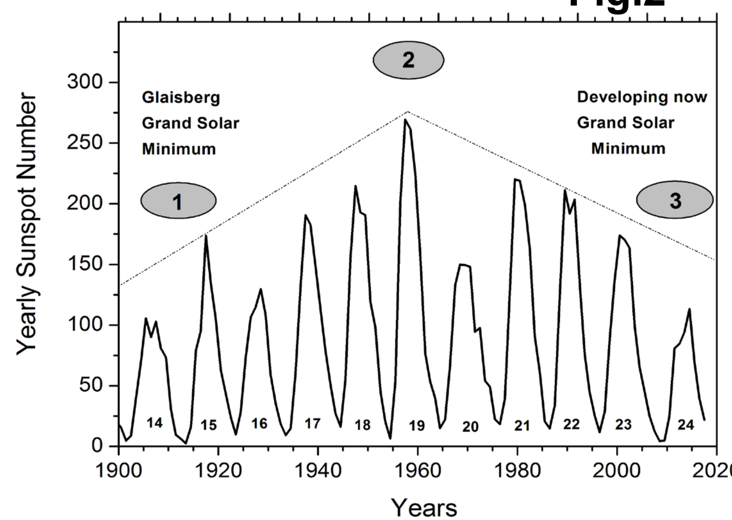


Fig.2



Comparison of time distribution of earthquakes with magnitudes M≥8.0 and yearly sunspot numbers since 1900 (**Fig 1** and **Fig 2**, respectively).

Variations of solar activity and occurrence of earthquakes with M≥4.5

Earlier [*Khachikyan et al., 2014*], investigated a dependence of earthquake counts and seismic energy released at the planet in 1973-2011yrs with using the data on earthquakes with M≥4.5 (182933 events) from the USGS seismological catalog http://earthquake.usgs.gov/neic.world.epic, and data on solar activity (sunspot numbers –SSN) from (http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber). It was found (**Fig.3**) that long-term trends in analyzed parameters are in counterphase: the yearly mean SSN decreases from 1973 to 2011 (black curve), while the yearly earthquake counts increases (gray curve). It is also found **(Fig.4)** that the deviations of earthquake counts from a trend are mostly positive close to minimum of the solar cycle, when the flux of the Galactic cosmic rays is expected to be increased, it is the mostly negative in moderate solar activity, but only slightly negative close to cycle maximum, when the flux of Solar cosmic rays is expected to be increased. Released seismic energy (**Fig.5**) demonstrates increasing for low solar activity, while a steady state decreasing for a moderate and high solar activity (strongest earthquakes in 1973-2011 preferred to occur in small solar activity).

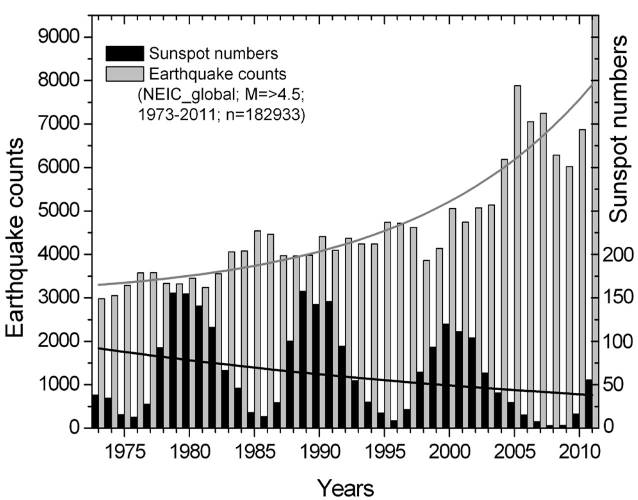


Fig.3. Black columns – the yearly mean sunspot numbers for 1973-2011 (182933 events), gray columns – the yearly number of earthquakes with M≥4.5; black and gray curves represent theirs long-term exponential trends.

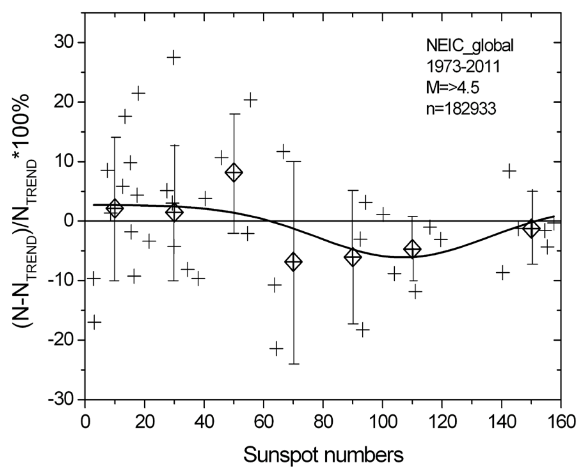


Fig.4. Crosses – the deviations from a trend the annual number of earthquakes (in percents) versus yearly mean sunspot numbers (SSN); diamonds - statistical deviations within bins of SSN=20; bold curve - approximation of deviations with the Gauss function.

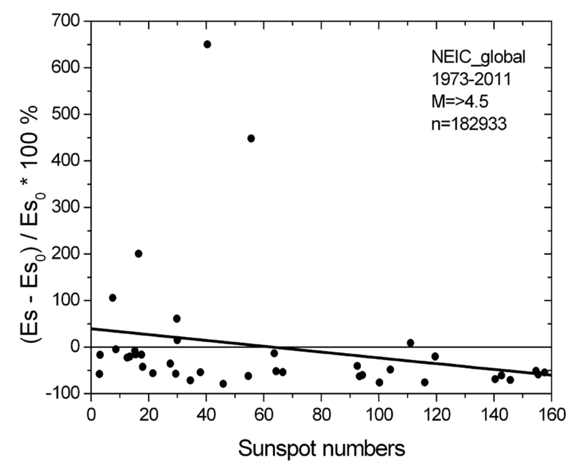


Fig.5. Distribution of relative seismic energy (in percents) versus yearly mean sunspot numbers (circles), line is a linear trend.

Paleo-earthquakes at Northern Tian-Shan and solar activity

Recently [*Zhantayev et al, 2020*] have analyzed a palioseismicity at Northern Tien Shan in connection with a paleo solar activity as reconstructed by the radiocarbon method ^{14}C to a depth of ~ 1000 years [*Usoskin et al, 2007*]. In bottom of **Fig.6,** horizontal lines mark possible periods of discovered paleo-earthquakes, and vertical lines indicate peaks in close grand solar minima. Four paleo-earthquakes: in area of Alakol lake at ~ 910 ± 300yrs [*Campbell et al., 2013*], in tectonic zone of Issyk-Ata fault at ~ 1385 ± 100 [*Patyniak et al., 2017*], in Chon-Aksu river valley in (1480–1660 yrs) [*Abdrakhmatov et al., 2013*], and in vicinity of Balkhash lake at Lepsinsk Fault in 1715 [*Campbell et al., 2015*] are closely related (with taking into account errors in paleo data) to solar grand minima: Oort (~ 1040 ± 30), Wolf (~ 1305 ± 35), Sporer (~ 1470 ± 80) and Maunder (~ 1680 ± 40), respectively.

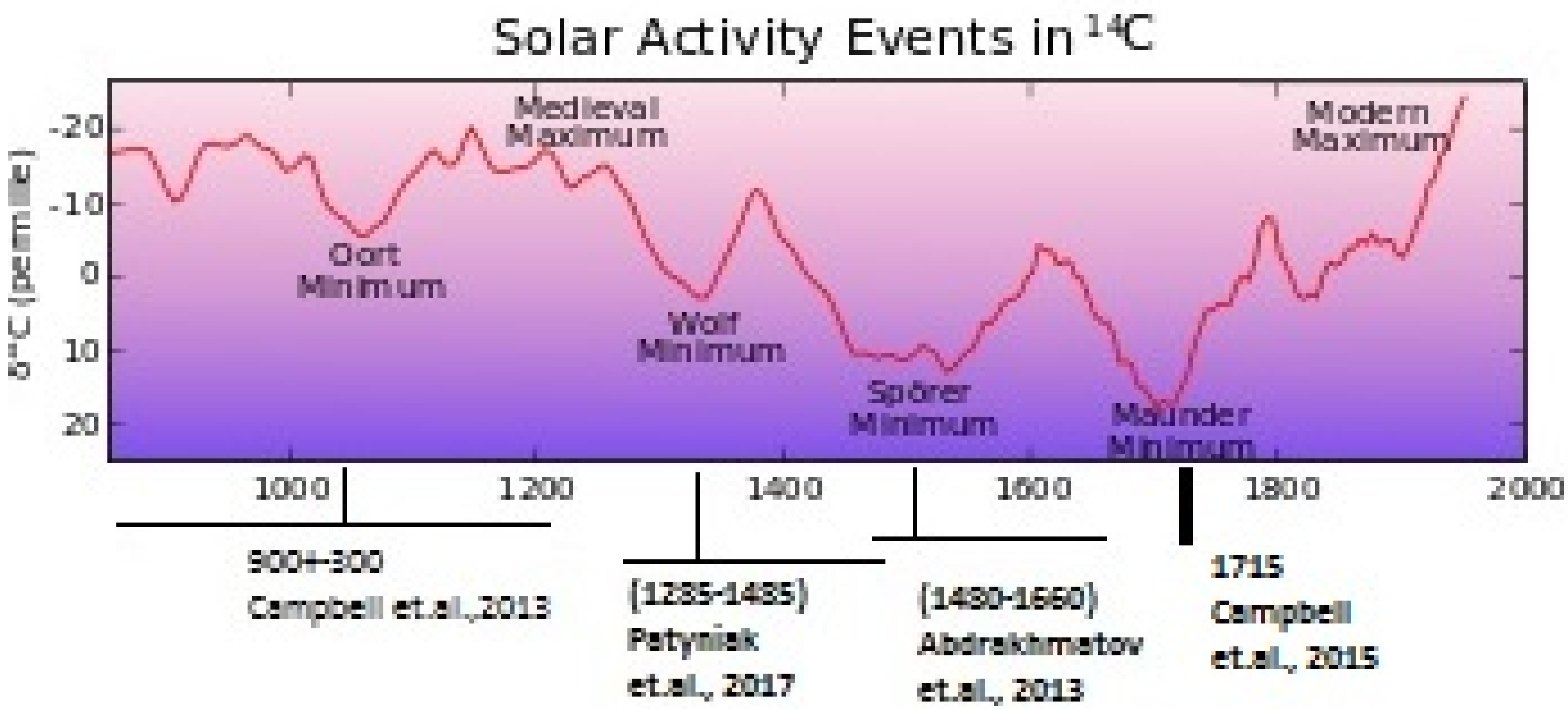
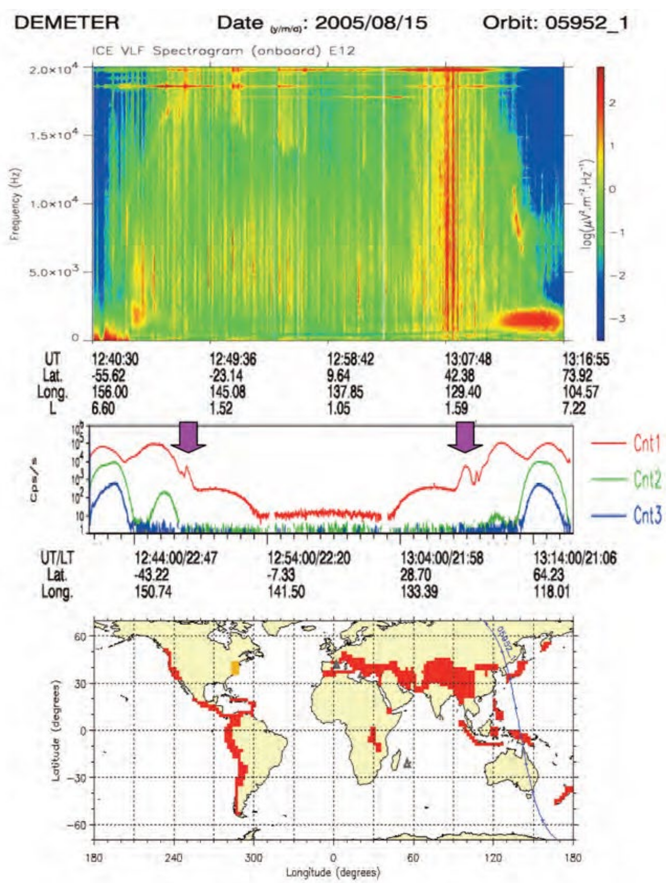


Fig.6. Variations of solar activity in 900 - 2000 AD reconstructed by the radiocarbon method ^{14}C from (https://en.wikipedia.org/wiki/Solar_cycle), and paleo-earthquakes in Northern Tien Shan.

The flows of high-energy charged particles associated with earthquakes

In fact, it is known for a long time that strong earthquakes may be preceded by charged particles bursts [*Ginzburg et al. 1994, Galper et al. 1995, Aleksandrin et al*., 2003, *Pulinets and Boyarchuk 2004, Anagnostopoulos et al., 2012, and references therein*]. For example, figures in below present the results from [*Anagnostopoulos et al.,* 2012], where the observations from the DEMETER satellite about half a day before M7.2 earthquake of August 16, 2005, in eastern Honshu, Japan (**Fig.7),** and before M8.8 earthquake of February 27, 2010, in Chile (**Fig.8**). In figures, **(a)** - spectrograms of electric field in frequency range 0 kHz to 20 kHz; **(b)** - intensity of electrons from the IDP experiment in energy regions of 72 keV to 526 keV, 526 keV to 971 keV, 971 keV to 2350 keV, and **(c)** - the DEMETER orbit projected on an Earth map. **Bold arrows in panels (b) mark two electron bursts at middle latitudes, with one burst above the future epicenter and a conjugate one in the other hemisphere.**

Fig.7



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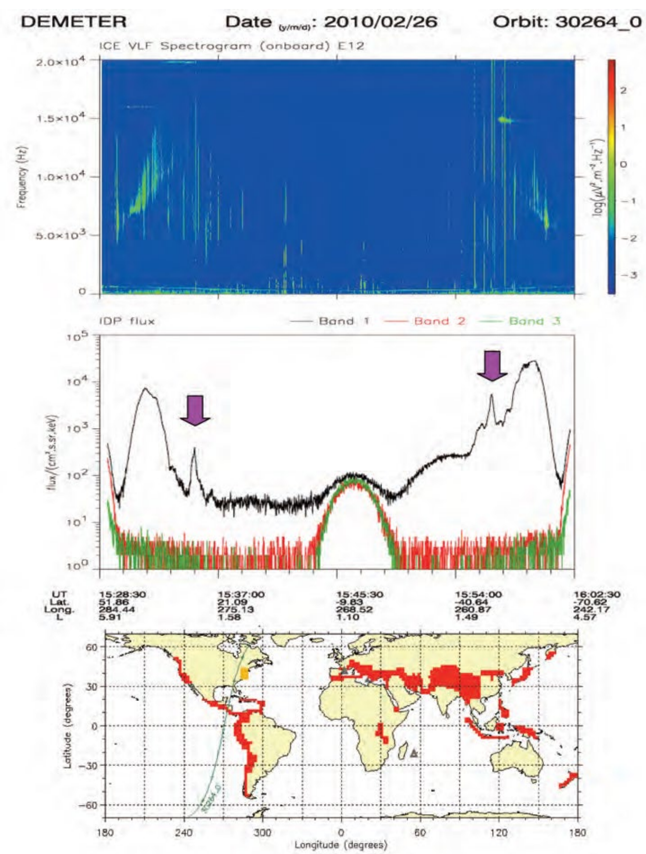

Fig.8

New results on correspondence between dynamics of radiation belt and seismic activity

In addition to above results we show, that about two months after the geomagnetic storms, which are followed by creating new radiation belts in a slot region or inner magnetosphere, seismic activity may increase near the footprints of geomagnetic field lines belonging to a new radiation belts. **For example:**

1) After geomagnetic storm on 3 September 2012, the satellites “Van Allen Probes” detected a new belt of relativistic electrons around of *L*=3.0–3.5 (**Fig.1**). In October 2012, seismic activity strongly increased in footprints of *L*=3.0-3.5 (**Fig.2**), on 28 October 2012, a series of earthquakes with M>5 occurred near Canada (**Fig.3**) with the strongest one M7.8 at 52.79^{0}N, 132.1W that is near the footprint of *L*=3.32 which belongs to a new belt of relativistic electrons.

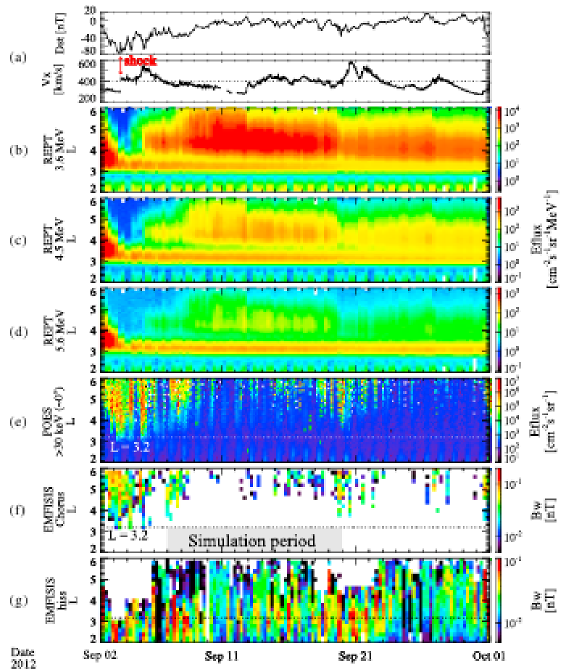

Fig. 1. Creating a new belt of relativistic electrons in radiation belt around geomagnetic field lines of *L*=3.0–3.5 after magnetic storm on 3 September 2012 from [*Thorne et al*, 2013].

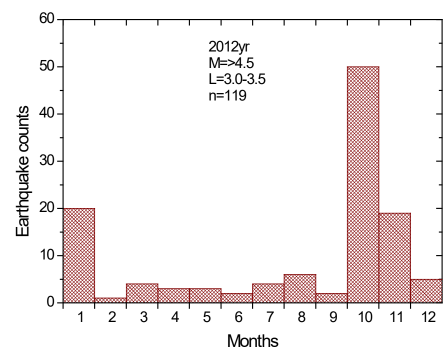

Fig.2. Monthly distribution of M≥4.5 earthquake counts in 2012 that occurred near the footprint of L=3.0-3.5.

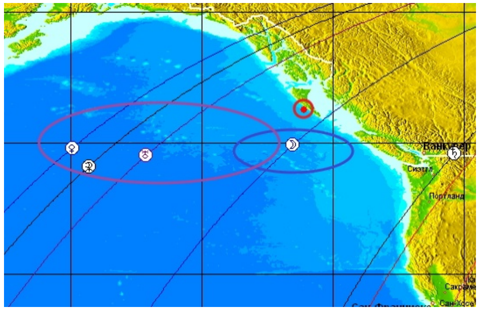

Fig.3. The series of earthquakes with M>5.0 occurred near Canada on 28 October, 2012, with the strongest one M7.8 at 52.79^{0}N, 132.1W that is near the footprint of geomagnetic line *L*=3.32

New results on correspondence between dynamics of radiation belt and seismic activity (*continue*)

2) The satellite "CRESS" observed a new belt of charged particles around L~2.6 after magnetic storm on March 24, 1991 [*Blake et al,* 1992]. Analysis of seismic data in footprints of L=2.5–2.7 showed increasing seismic activity in May 1991 **(Fig.3)** that again ~2 months after the magnetic storm onset. The strongest event M7.0 occurred on 30 May 1991 in Alaska (54.57^{0}N, 161.61^{0}E) that is near the footprint of L=2.69 which belongs to a new radiation belt.

3) The satellites "Van Allen Probes" detected a new belt of relativistic electrons around of L=1.5–1.8 after magnetic storm on 23 June 2015 [*Claudepierre et al*. 2017] **(Fig.4).** Analysis of seismic data in footprints of L=1.5-1.8 showed (**Fig.5**) that seismic activity was here strongly increased in September 2015, that is some more of 2 months after geomagnetic storm onset. Line in bottom of **Fig.4** marks the date of strongest M8.3 earthquake occurred on September 16, 2015 in Chilli. It occurred near the footprint of L=1.12, which was strongly populated in that time by the KeV electrons [*Baker et al. 2018*].

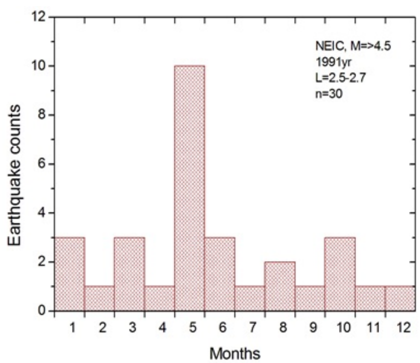

Fig.3. Monthly earthquake counts in 1991 near the footprint of L=2.5–2.7.

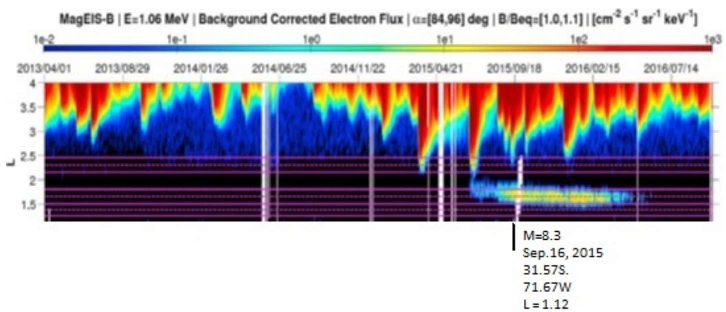

Fig.4. Creating a new belt of relativistic electrons around of L=1.5–1.8 after magnetic storm on 23 June 2015 from [Claudepierre et al. 2017]. Line in bottom marks date of strongest in the 2015 year earthquake on September 16 in Chilli with magnitude M=8.3.

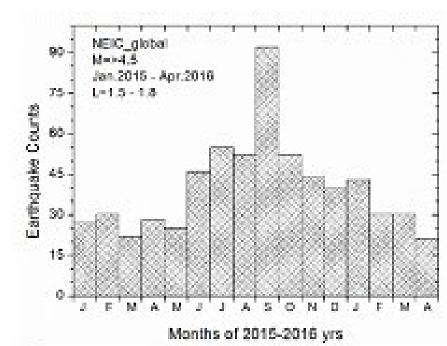

Fig.5. Monthly earthquake counts from January 2015 to April 2016 near the footprint of L=1.5-1.8.

Conclusion

- Clustering periods of the planet’s strongest earthquakes (magnitude M8 or more) at the beginning of the 20-th century, in the middle and at the beginning of the 21st century have fallen into periods of the extreme states of solar activity: solar grand minimums at the beginning of the 20th and beginning of the 21st centuries, when the flux of the Galactic cosmic rays is increased, and the solar grand maximum at the middle of the 20th century, when the flux of solar cosmic rays is increased.

- Data on earthquakes with M≥4.5 occurred at the planet in 1973-2011 (182933 events) show sufficient increasing their amount in low solar activity, when the flux of the Galactic cosmic rays is increased, and small increasing in high solar activity, when the flux of the solar cosmic rays is increased relatively to the moderate solar activity.

- Strong paleo-earthquakes in the Northern Tien Shan to a depth of ~1000 years, gravitated to the periods of solar grand minimums: Oort, Wolf, Sperer and Maunder, when the flux of the Galactic cosmic rays is expected to be increased.

- We speculate that both the cosmic rays and the high energy particles precipitating from the radiation belt in times of strong geomagnetic storms may be a trigger of earthquakes, and present some experimental results which support this speculation, it is shown in particular:

- The DEMETER satellite about half a day before strong M7.2 earthquake of August 16, 2005, in eastern Honsu, Japan, and before giant M8.8 earthquake of February 27, 2010, in Chile, detected relativistic electron bursts at middle latitudes, with one burst above the future epicenter and a conjugate one in the other hemisphere.

- The process of emptying the external electronic radiation belt by a geomagnetic storm, followed by the formation of a new (additional) radiation belt in the inner magnetosphere is accompanied, after about two months, by an increase in seismic activity near the footprint of the geomagnetic lines of the new radiation belt.

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