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Review Article

Space Seismology

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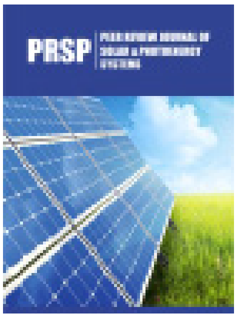
Abstract

The typology of the different seismic events observed on the Earth, Moon, Mars and Sun is presented. Despite the origin of seismic events on the terrestrial bodies are expected to be similar, the missions to the Moon and Mars equipped by seismological apparatus, show significant differences in the space-time distribution of the seismicity, as well as the sources of the Moonquakes and Marsquakes. The Suh have different composition but Sunquakes are also observed. The review and comparison of the seismicity of the Earth and extraterrestrial objects are performed and similarities and differences outlined. The conclusion is that we have rather limited knowledge about the seismic processes on the other terrestrial objects, than to the Erath.

Keywords: Space seismology; Typology; Earthquakes; Moonquakes; Marsquakes; Sunquakes



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Introduction

The space seismology is a new emerging science discipline studying the seismic events and their properties on the extraterrestrial objects. Its targets are to study the generation mechanism, the seismic waves' propagation and the interactions between the seismic waves and the properties of the substances they propagate. The seismic events are typical for the sudden destruction of the solid substances elsewhere (on Earth, Moon and Mars in particular).

Earthquakes, Moonquakes and Marsquakes are a clear expression of the strata stress release on these terrestrial cosmic bodies. Due to this property these seismic events generate seismic waves which are the most important source of information for the internal structure of the planets and their satellites (if they are solid bodies) and the respective dynamics of their geology evolution. According the recent scientific research of the terrestrial bodies almost all initial space missions include in their scientific programs installation of seismometers and telemetric transfer of information.

Almost all missions to the Moon and Mars including seismic studies are successful and the data provided show expected similarities and surprising differences of the registered seismic events [1]. Comparisons of these similarities and differences are important and can help the understanding of seismic processes on the space terrestrial studied bodies. And this is the main aim of this study, including typology, similarities and differences of the Earthquakes, Moonquakes and Marsquakes. The Sunquakes have completely different origin but also show the wave propagation on the Sun surface.

It is important to mention that every seismic event is in fact the sudden stress (accumulated in solid strata) release in a very short time followed by the propagation of the seismic waves. The seismic waves are body-waves (P-primary and S-secondary) and surface waves (Raleigh and Love-named to their discoverers). The S-waves do not propagate trough fluids and this property is frequently used for the deep planetary interior study. These waves are registered by seismographs (broadband, short period, accelerometers, etc.) on the seismogram and the final part (tail) of the seismogram is called "coda". The Sunquakes consist mainly of Raleigh waves and propagate in fluids. The last ones are observed by distance, without direct measurement on seismograms.

Material and Methods

Data and observations collection

The instrumental seismic observations on the Earth covered about 150 years' time interval, since first seismic stations installed in 1890-ties in Japan and other seismic prone countries. Now a huge extensive seismic equipment is dispersed all over the world with more than several thousand seismic stations - (broadband seismic, accelerometers and tide gouges) and short period's (usually velocity graphs), providing registration of seismic events from very small (negative) magnitudes to the major catastrophic earthquakes all over the globe. The magnitude scale is "open", but the physical properties (mainly stress accumulation ability) of the Earth's crust limit the upper boundary of strongest magnitude to about 10-11 Richter scale. First seismograph on Moon was installed by Apollo 11 mission in 1969. All astronauts' missions of Apollo studied the moonquakes by several seismic stations and array. The registration of moonquakes was switched-off in 1977. The total number of seismic events on the Moon are over 12-13 000 [1]. First measured by NASA's InSight lander on April 6, 2019, marsquake was one of the lander's key science goals, achieved successfully. Up to now more than 1700 marsquakes are registered on Mars surface.

Typology of the seismic events

On earth: A short description of earthquakes includes:

a) Tectonic earthquakes-due to the tectonic forces in different geodynamic regime: extension (in the rift zones)-produce normal faults; compression (subduction zones)-produce trust faults; blocks' interactions (transform faults)-produce strike-slip faults; huge rock's layers horizontal sliding-produce listric faults and all possible combinations related to the stress accumulation release [2] (Figures 1 & 2).

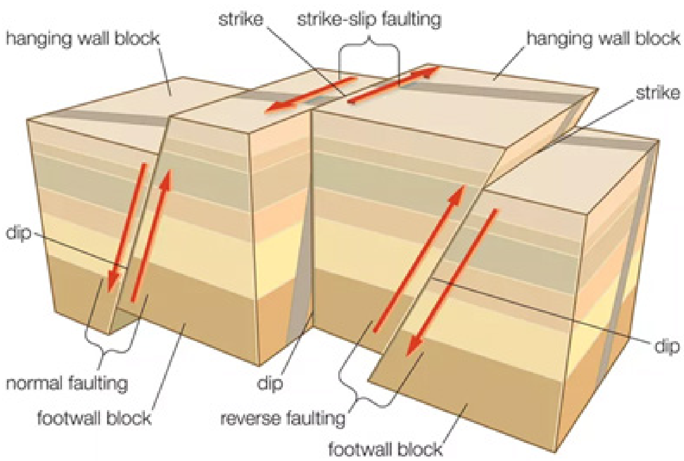

Figure 1: Schema of blocks and different types of movements on the faults-classical seismology [2].

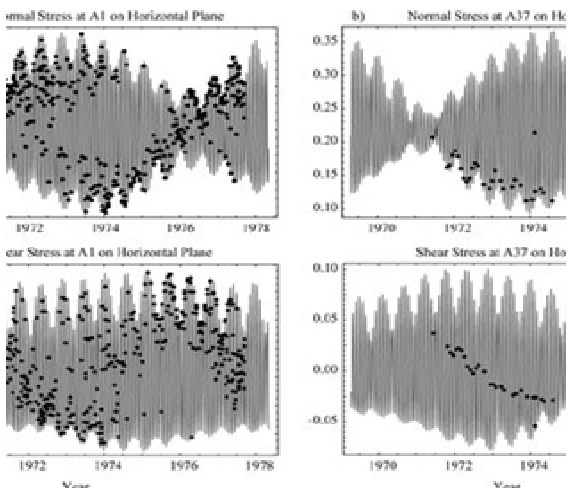

Figure 2: Correlation between deep moonquakes and solar-terrestrial tides.

b) Volcanic earthquakes-swarms of earthquakes, generated by magma movements in the magma chamber of the active volcanoes.

c) Collapse earthquakes-due to huge collapses in caves and mines.

d) Tide's earthquakes-due to the Erath's tides generated by Sun-Moon gravity effects to the solid earth.

e) Meteorite impacts-(Impact craters-astroblems)-mostly preserved ancient craters. Over 200 major astroblems are detected on the Erath's surface

f) Induced earthquakes-due to the human activity-dams filling, blasts (including nuclear explosions), liquid extraction or pumping, rock bursts, hydraulic fracking, etc.) Earthquakes are conditionally separated by depth in dependence of their occurrence as "shallow" (depths between 0 and 33km-in the earth's crust), intermediate (depth between 33 and 300km) and deep (between 300 and 760km) in the earth's mantle. The power of earthquakes is usually measured by Richter scale.

On moon: Surprising results about moonquakes were obtained during the Apollo missions and the seismic registrations on the Moon [1] (Figure 3). According their depth of occurrence they have been divided as "deep" and "shallow" moonquakes and according their origin as:

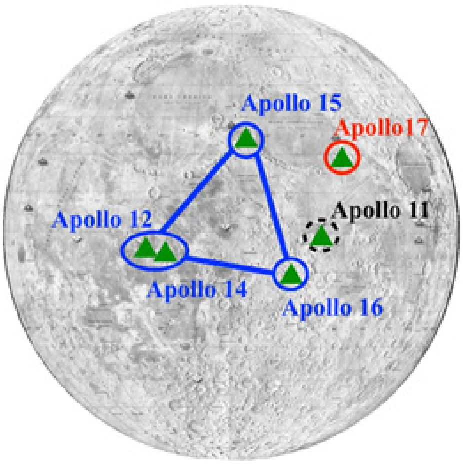

Figure 3: Locations of the landing sites of Apollo's and seismometers disposition [1].

A. Natural moonquakes - deep and shallow. Deep moonquakes (~700km below the surface,) are considered to have most probably tidal in origin (Figure 2). Shallow moonquakes occurred 50-220 kilometers below the surface, some of them at depths up to 30km. The shallow moonquakes occurred at the depth interval 30-200km (it's upper mantle but not in the Moon's crust). The origin is not very clear (the scientists supposed that they are due to the contraction of the moon during the cooling of the interior of the satellite). There is relative similarity with the intraplate earthquakes in their occurrence. The stress-drop is enormous most probably due to the destruction of the rock substance at the deep interior. There is no correlation between tides and shallow moonquakes.

B. Thermal moonquakes (the frigid lunar crust expands when sunlight returns after the two-week lunar night). Thermal dependence for the thermal moonquakes due to the sunrise and sunsets is important. The surface temperature changes are +120 ˚C to -130 ˚C. The seismic events due to heating-cooling effect occurred in the very shallow depths, have low magnitudes and low expected intensities. They have relatively short lasting vibration signal.

C. Meteorite impact vibrations (generated by the hits of meteorites on the Moon surface). Eleven hits by meteorites over 1 ton have been registered [3].

D. Artificially generated seismic events by blasts and kicks. In general 9 active artificial shocks have been performed (hitting by lunar module, blasts or human hits). Artificially generated seismic waves have been made in 2 specially designed active experiments of the mission Apollo 17. One of them used linear disposition of 3 broadband seismometers at distances 45.7 meters. Another was triangle shape area of 4 geophones (velocitymeters) with distances of 50-60 meters between them [4].

E. What is important to mention is that the seismic signals attenuate many times less than in the Earth (Figure 4). This means that the quality factor is higher than on the Earth. Considering the fact that the surface mineral composition is dominated by anorthosite (rich of Calcium alumosilicate) it means that the Moon sounds as a giant glass sphere, resonating to the seismic waves much more intensive than on Earth. That's why the seismic waves attenuate less than on Earth and the coda waves are much longer on seismograms of the moonquakes. The power of moonquakes is usually measured by Richter scale calibrated to the earth's conditions. Observed moonquakes (Figure 5 & Figure 6) have been mostly less than 3 on the Richter scale; the largest recorded ones have a magnitude between 5 and 5.7 (Mmax). Shallow moonquakes can register up to mb=5.5 on the body-wave magnitude scale. Between 1972 and 1977, 28 shallow moonquakes were observed - less then all others. Deep moonquakes tend to occur within isolated kilometer-scale patches, sometimes referred to as nests or clusters. The power spectrum of vibrations is in the frequency domain of 0.5-8Hz. The high stress drop is typical for the moonquakes of any type [5-7].

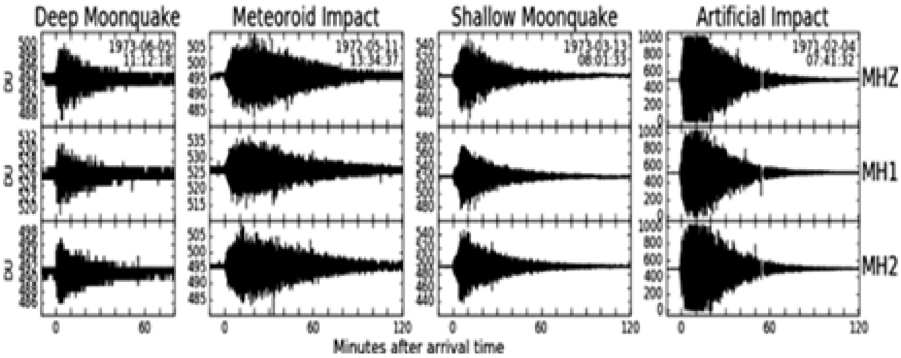

Figure 4: Typical seismograms of Moonquakes (note the length of vibrations) [1].

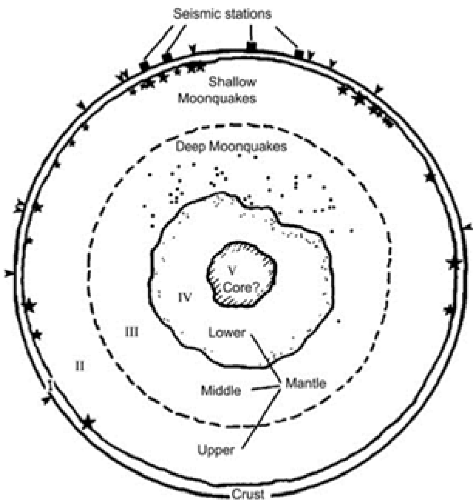

Figure 5: Depth distribution of Moonquakes [3].

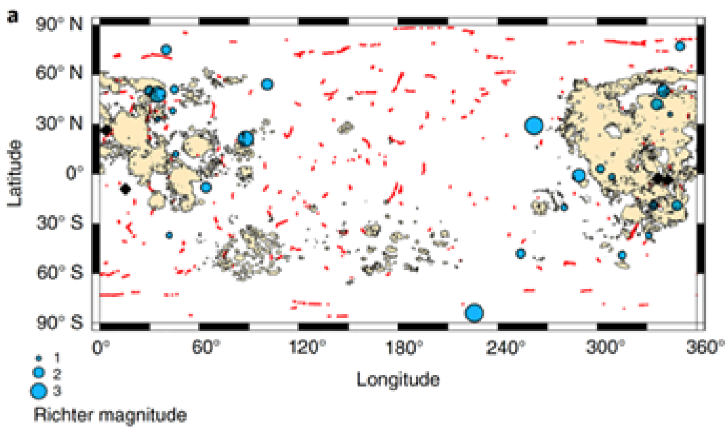

Figure 6: Spatial distribution of some moonquakes [4].

On mars: Marsquakes are registered mainly by the NASA mission InSight. Over several hundreds of marsquakes were detected with the larger magnitudes around 4-4.7. In total more than 1 500 marsquakes were registered (Figure 7). For the relatively short period of the InSight mission these numbers of seismic events demonstrate that the Mars is a moderate seismic active planet - much more active than the Moon (excluding deep moonquakes), but less than the Earth. In general the frequency domain of the registered seismic waves is between 0.4-1.0 Hz and 0.2-0.4Hz (Figures 8 & 9). This means the domination of relatively low frequencies and fast attenuation of the seismic signals. Up to the present day only crust seismicity of Mars is registered (Figure 7). These seismic events were used in general to prove deep Mars interior showing very similar to the Earth marsodynamics-molten core, solid mantle, active crust with a lot of formerly active volcanoes. High frequency events are usually related to the extensional marsodynamics and are shallower. Low frequency marsquakes are most frequently connected with compressional regime. All marsquakes are considered that the generation mechanism is due to the cooling effect of the planet, which still is in development. The strongest marsquake recorded up to now, which had a magnitude of 4.7 and caused vibrations to reverberate through the planet for at least six hours, was recorded by NASA's InSight lander on May 4th, 2022 (Figure 10). This seismic event is considered as very strong for the Mars conditions.

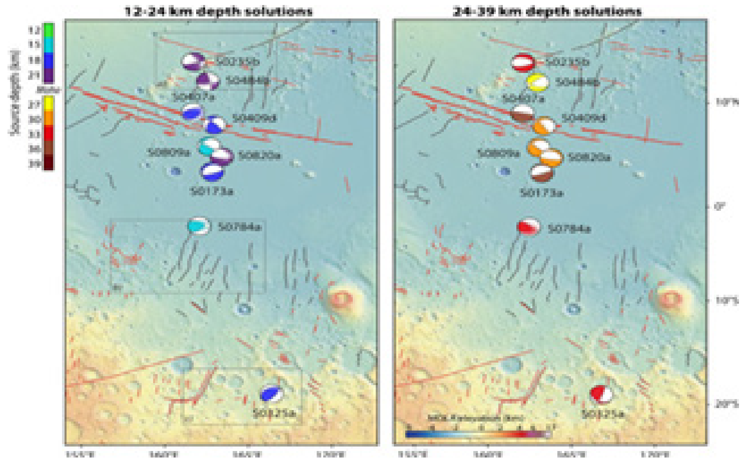

Figure 7: Most seismic events are tectonically related to the faults–just as on the Earth [5].

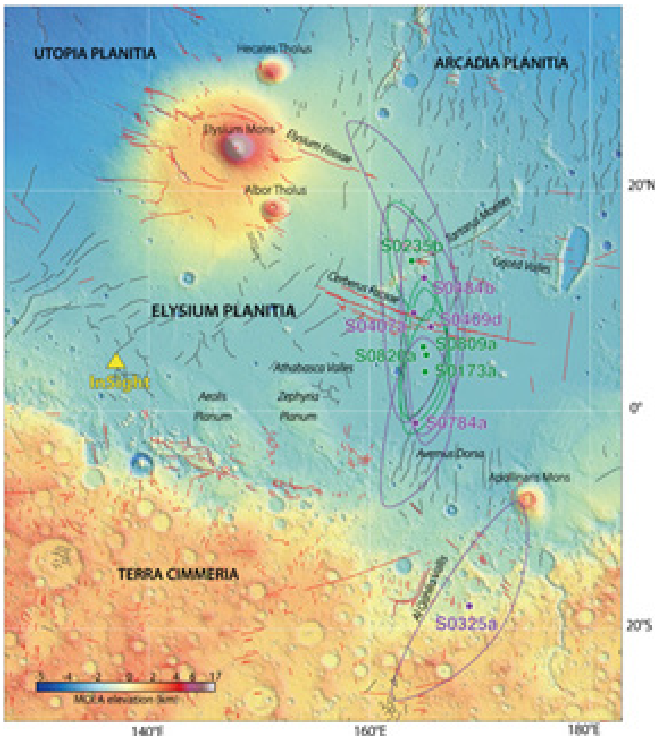

Figure 8: Low frequency events <2.4 Hz (green) and high frequency events >2.4 (purple) [5].

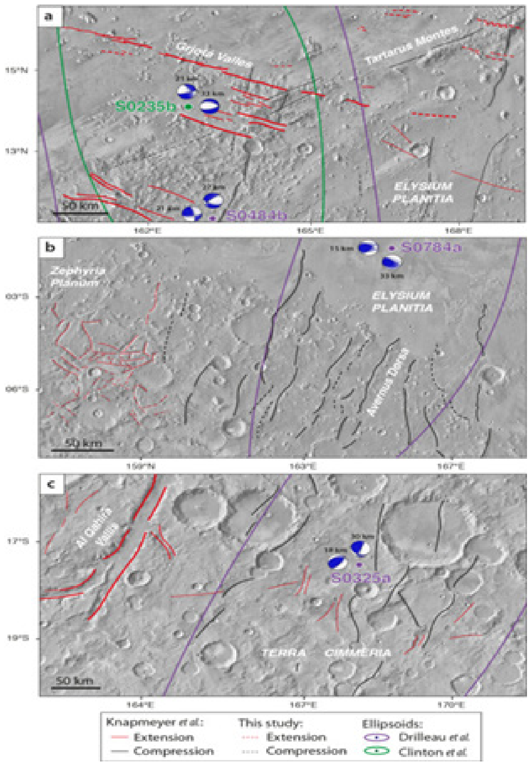

Figure 9: Extensional (red) and compressional (black) faults and marsquakes [5].

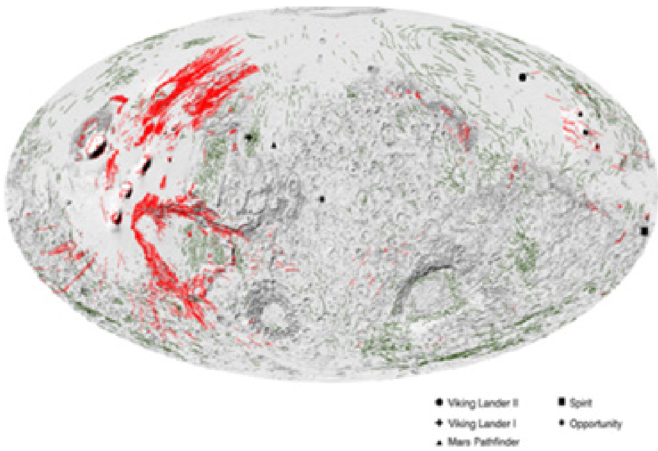

Figure 10: Global distribution of the Mars' zones of compression (red) and extension (green) [6].

The stresses accumulations are considered as the result of billions of years of evolution; including the cooling and shrinking of different parts of the planet at different rates. It is still not fully clear why some parts of the planet seem to have higher stresses than others. One day, this information may help to understand where it would be safe for humans to live on Mars and where they have might want to avoid!

Two meteorite huge impacts have been registered by InSight seismometer proving the surface seismic waves propagation and for first time documented on another planet [8]. The power of Marsquakes is usually measured by Richter scale, calibrated to the earth's conditions.

Seismogenic sources are mostly visible structures of the central Elysium Planitia region where InSight landed. They are fractures and faults, ranging from a few tens of kilometers to several hundred kilometers long [6]. In general two main models of deformation are observed, extension (red lines) which is dominant in the region, and compression (black lines) (Figure 10). The surface temperature fluctuations vary between +200C to - 1500C, but clear influence of heating-cooling effects are not registered. Mars fractures and faults have been mapped by several missions (Viking 1 and 2, Pathfinder, Spirit and Opportunity) thus providing rather clear picture of the zones and compression and extension (Figure 8). The reason for such distribution of the Mars crust stress is still unclear. The scientists propose the contraction hypothesis, but not all details of it can explain all peculiarities. The largest marsquake was registered on May 2022 [7] (Figure 11).

On sun: Several seismic events have been recorded on the solar surface. They are associated with powerful eruptions of ssolar plasma. They form concentric seismic Raleigh waves similar to those caused by a falling stone in a pool of water. Only, the source comes from below, like a bursting soap bubble (Figure 12). This section may be divided by subheadings, sub-sub headings. Provide sufficient details to allow the work to be reproduced by an independent researcher. Methods that are already published should be summarized, and indicated by a reference. Any modifications to existing methods should also be described.

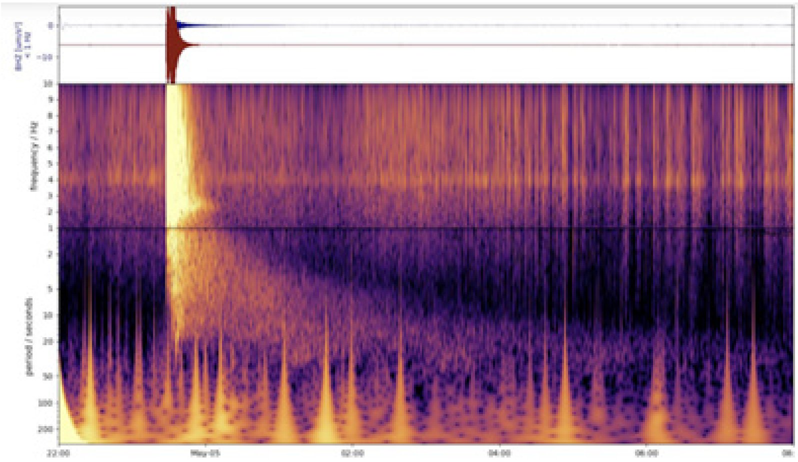

Figure 11: Seismogram of the marsquake (M4.7) registered on May, 2022 and frequency spectrum [7].

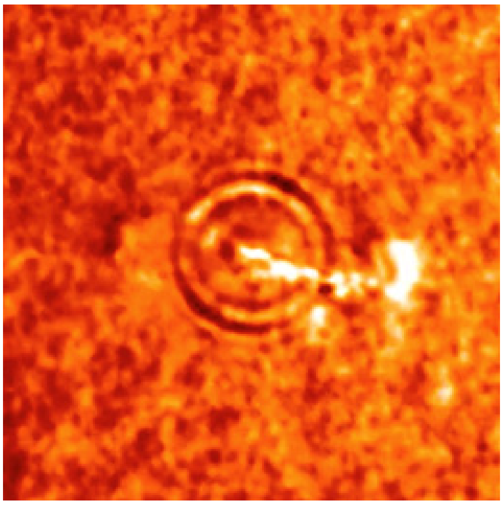

Figure 12: Typical sunquake due to the plasma eruption.

Results

Extraterrestrial seismic events-comparison with earthquakes

A comparison table with the main parameters of the observed and registered seismic events in the Solar system is constructed (Table 1). The table presents the main seismological parameters focusing to the origin of known events, depth, magnitude and percentage of seismic registrations on Earth, Moon, Mars and Sun. To compare the seismic activity and seismic events nature for all extraterrestrial registrations a table is created, which deals with the specifics (similarities and differences) of all types of seismic events registered on Earth, Moon, Mars and Sun. The lower diagonal part of the table identifies the similarities, and the upper diagonal part-the differences in very short and essential form pair by pair. Results should be clear and concise and also separate from the Discussion part. Each Tables and Figures must be found below their respective paragraphs from the Results part (Table 2).

Table 1: Seismic events of all types and their main seismological properties.

Main Parameters/Type of Seismic Events	Source	Depth [km]	Magnitude (Mmax, Richter)	~ % of Registrations
Earthquakes:				
tectonic	Tectonic forces	0-780	-1 to 9.6	95-96
volcanic	Volcanic activity	0-3-5 (crust)	-1 to 5-6	2-3
collapse	Caves, mines	0-1 (crust)	1 to 4-5	0.3-0.4
tide	Sun-moon tides	0-10 (crust)	0 to 3-4	0.2-0.3
meteorite	Impact	0-0.5	3 to 5 (astroblemas-rare)	0.1-0.2
induced	Human	0-1-3 (crust)	0 to 6	0.5
Moonquakes:				
thermal	Day-night change	0-0.1-0.2	1.0-3.0	0.1
tide (very clear coincidence)	Sun-Earth gravity	Deep (240-700)	5.0-5.7	90
meteorite	Impact	0-1	1.0-5.0	7
induced	Human	0-0.01	5.0-5,2	~0.1
cooling	Contraction	Shallow (30-320)	5.0-5.5	02-Mar
Marsquakes:				
tectonic (extension)	Stress-release	Crust (10-20)	1-4.7(strongest)	50-70
cooling (compression)	Stress-release	Crust (20-40)	2.0-4.0	30-50
Meteorite (rare)	Impact	0-0.5	0-5.0 (for now)	~0.1
Sunquakes	Plasma burst	0-1000 (~more)	5-6 - 12-14 (huge energy release)	all

Table 2: Differences (upper) and similarities (lower) part of the table presents the comparison between Earthquakes, Mars quakes, Moonquakes and Sunquakes.

Differences / Similarities	Earthquakes	Moonquakes	Mars Quakes	Sunquakes
Earthquakes	Same	Thermal and tidal activity. "Nests" for deep events. Very high stress drop. Long lasted coda waves.	Higher intensities for same magnitudes. Long lasted coda waves.	Completely different due to the specific origin (plasma plumes)
Moonquakes	Missing (except meteorite impact and part of tidal and induced events). Shallow are similar to intraplate events (without clear tectonic activity)	Same	Missing thermal and tidal activity. Still missing induced events.	Completely different due to the specific origin (plasma plumes)
Mars quakes	Tectonic origin. Faults related. Meteorite impacts.	Contraction as reason of limited seismic events. Meteorite impacts.	Same	Completely different due to the specific origin (plasma plumes)
Sunquakes	No similarities observed due to the plasma plumes	No similarities observed due to the plasma plumes	No similarities observed due to the plasma plumes	Same

Discussion

The concentric structure of the Earth, the Moon and Mars, established by the propagation of seismic waves and the confirmed different envelopes of the studied bodies, reveal the structure and, together with other natural physical fields (such as magnetic, gravitational, radioactive and thermal), enable comparing and studying the shape of the internal structure and a more detailed study of the dynamics in the depth structure of the bodies (Figure 13).

Much more interesting are the unexpected differences in the seismicity of the studied extraterrestrial bodies (in our case, the Moon and Mars) when compared to the seismicity of the Earth. As an immediate property of geodynamics, seismicity is the most recent part of geodynamics and its most active ingredient. The structure and evolution of the Earth predetermine the high seismic activity of our planet. The plate tectonic paradigm is a powerful tool for studying modern geodynamics. The moon and moonquakes are different in many ways. High seismicity, due to the change of day-night heating and cooling of the lunar crust, is the main source of surface seismic activity of the Earth's satellite. The tidal effects of the Sun-Earth impact on the Moon are another surprise to science. Coincidence in the timing and phases of gravitational interactions is another powerful source of seismicity on the Moon and occurs at greater depths. Shallow (50-240km) moonquakes, even very few in numbers, are still an enigma and do not yet have a clear explanation. Another very strange property is the long lasted vibrations after each moonquake. They are 5-10-20 times longer than terrestrial ones. This is probably due to the chemical composition of the lunar crust (with a higher anorthosite content), but this has not yet been explicitly confirmed.

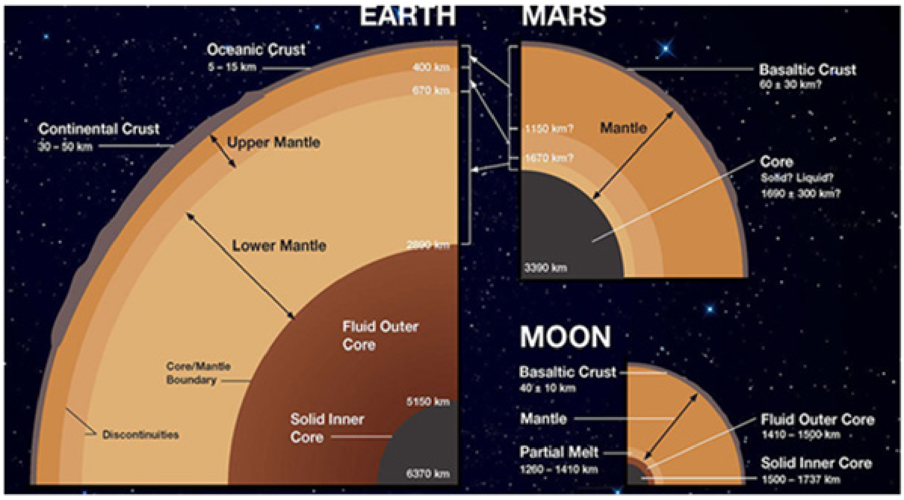

Figure 13: A comparative diagram of Earth (left), Mars (top right) and the Moon (bottom right) shows the internal structure of terrestrial bodies established and clarified by seismic exploration of recorded seismic activity.

Regarding Mars and Marsquakes, they also have surprising elements [5,6]. Even clearly related to fault structures (extensional and compressional), Marsquakes also demonstrate long-lasting coda waves, and for a relatively small seismic event (M4.7 from Earth's perspective) the reverberation on Mars for about 6 hours after an earthquake is another very surprising fact. This indicates that such events can be reported as strong for the Martian environment. The lack of evidence for a tidal effect on Mars is another enigma. As a smaller body than Earth, the tides generated by the Sun and Earth are expected to generate tides on Mars, but so far no such correlation has been observed. Extensional and compressional quakes also suggest more active internal dynamics on Mars (probably similar to Earth's geodynamics). This has not yet been confirmed and the tremors are considered to be fault-related phenomena [9].

In the perspective of space missions to the other planets, seismic activity could be expected in the Earth-like planets - Venus and Mercury, as well as on some moons of the other planets. The gas giants may possibly exhibit earthquake-like Suntremors accordingly. In conclusion and in short, surprises are unexpected and future research may yield new and interesting results regarding the seismicity of extraterrestrial bodies.

Conclusion

A comparative review study presents the similarities and differences of seismic activity of the Earth, Moon, Mars and Sun. New and surprising results are outlined explored as well as by other authors and publication. The Moonquakes have similarities (solid substrate destruction) and differences (long lasted coda waves, different origin of some Moonquakes (temperature variations) and lack of Moon deeper dynamics in comparison with the Earth. The Mars quakes also have similarities (solid crustal substrate destruction) and differences (lack of Mars dynamics and the source of Mars quakes are due to the contraction of the planet) in comparison with the Earth. All these comparative results are systemized in a Table for easy observation. The main achievements of this review is the comparison of the sources of seismic events, their properties extracted from the registrations, their power calibrated to the Richter scale and the percentage distribution according their generating mechanism.

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