How our planet fate is governed by "stars" - geological record of cosmic impacts on terrestrial processes

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Material cycling on the Earth surface is controlled by extraterrestrial physical forces – the effect of planetary motion vector, the gravity effect of the moon and nearby planets, and energy input fluctuations from our nearest star - the Sun. Their recognition in the past supports clarification of both the astronomical time scale and more detailed knowledge on forming process of the Earth and of the life on it.

The lithosphere, which is produced by the constant interplay of internal and external forces acting on its surface, recorded billion years long history of our planet. Tens of thousands meters thick sediments represent the record of geological time. It is not enough to read this record to follow the development of our planet, as our stone archive is stirred, containing many often unknown data, records are incomplete, and even a large parts of them are totally absent, so instead of a solid chronicle, the nature offers a lot of decayed, incomplete pages, often in mixed order.

Ancient interpretation of rock massifs led to a conclusion that the surface of continents is mutable, that the past still constantly undergoing radical changes. A detailed study of rocks and their arrangement come to knowledge of periodic repetitions of individual texture and structural composition of sediments. Thus, the formation of sediments involved a periodic repetition of environmental factors.

Hutton (1788) considered periodic uplift, erosion and accumulation of sediments in basins. Goethe assumed that the Earth climate is undergoing through changes and that the Europe overcame through era of a great cold in the geological past. Similarly, Agassiz (1840) argued that moraines in Alpine valleys have been covered by massive ice sheets (such as the Greenland of today). MacLaren (1842) recognized a link between glaciation and sea level fluctuation. Adhémar (1842) supposed that glaciations are triggered by a precession of the Earth rotation axis. Croll (1889) related eccentricity of the Earth's orbit with the precession of the Earth rotation axis and with resulting length of seasons. Based on carbonate content changes in Cretaceous hemipelagites from Colorado, Gilbert (1895) found that irregularities in the planet circulation may affect the amount of solar energy adopted by its surface. Penck and Bruckner (1929) suggested that four separate interglacial fluctuations of temperature took place during the Quaternary glaciation. Bradley (1929) recognized repetitions corresponding to precession cycles in oil shales from the Green River Valley of western USA.

Complex and increasingly recognized interpretation of astronomical factors ruling our planet has been given by Serbian mathematician Milutin Milankovitch (1941). It justifies climate impacts on the planet's surface through changing insolation and through mechanisms governing the energy transition through the atmosphere (Kneźević 2010). Secular eccentricity, precession and inclination changes of the Earth's orbit, of its rotation axis are the most important astronomical mechanisms that stimulate insolation changes. The eccentricity of Earth circulation over time changes due to gravitational pull of other planets. Changes are quasi-periodic, with different amplitude and events in different time slices.

From the beginning, the Milankovitch theory met skepticism of practical geologists. Later, Emiliano (1955) stated frequency of the isotopic record in Pleistocene marine sediments. Then, Hays et al. (1976) accepted the term “Milankovitch cycles” (with a frequency of 104 to 105 years) and its use as a tool for the interpretation of orbital periods.

The sun is the dominant factor in Earth's climate system: These cycles are driven by periodic changes of solar radiation. The intensity of sunspots fluctuates in short-term (11 years Schwabe- and 22 years Hale-) solar cycles that modulate ten- or/and millennial climate changes. Their geological record, however, is rare and limited by a special preservation. Formation of microlaminated sediment has been controlled by the solar activity cycles which ruled rates of microbial growth, biomass production, rainfall, temperature, redox, etc., leading to variations in elements (Ca, Fe, Br ...) concentrations during deposition and early diagenesis (Tang et al., 2014).

Rotational movement of the Earth's axis is changing in precessional cycles with a periodicity of 23.7 ky (thousands of years). Thus, rotational axis describes a cone with a top angle of 23.44°. If the precession cone angle changes to 54 °, average tropical temperatures will not change dramatically, but the climate in polar regions gets warmer (like 99 My ago during Mid Cretaceous; Michalík, 1999). The actual precession changes were defined already in Hipparchos sky map (150 y B.C). Copernicus (1543) correlated these changes with changing position of the Earth rotational axis. Change of its inclination to ecliptics (from 23.5° by about 3°) at intervals of about 41 (39.7 to 56.3) ka causes obliquity cycles. Sha (2015) came to the conclusion that higher latitudes of the Earth before 200 My (during Triassic / Jurassic interface) were influenced by orbital cyclicity, managed by obliquity (40 ka), while the obliquity record at lower latitudes is indistinct.

Quaternary ice ages were associated with eccentric cycles (interference with the Jupiter in periods of 100 ka and 405 ky). Eccentricity variation affects the distance to the Sun: the amount of solar radiation reaching the Earth is inversely proportional to the square of this distance. Thus, astronomically induced signal is recorded in continental and marine sediments in cycles that correspond with climatic changes. Martinez and Dera (2013) concluded that Early Jurassic transgressions and regressions and resulting productivity changes may reflect changes in sea-level driven eccentric cycles. The same authors

(Martinez et al., 2015) identified Early Cretaceous eccentric cycles (405 ky) in the Vocontian-Subbetic basins.

Depending on the degree of sensitivity to global climate turnover in a given period of time, each component is capable to cause significant climate change. Global seasonality is low in times of low obliquity (when the planet's rotational axis is almost perpendicular to the ecliptic plane), called as the “climatic optimum”, when long eccentric cycles are recorded in sediments. Conversely, when beveling the Earth's axis, temperature gradients and increasing seasonality are marked, polar regions became cooler. During this time, called as the “climate minimum”, short-term periodicities record is dominating. If a continent is in a polar position, equatorial oceanic current is blocked and seaway for circumpolar currents opens, atmosphere is depleted of greenhouse gases, solar activity is reduced starting the albedo effect, a way to glaciation is open.

Global oceanic/atmospheric currents that control humidity, rainfall and temperature are the main control element of the climatic regime. Atmospheric current system consists of Hadley, Ferrel and polar jet cells. Where circulation given by these three cells collides with the Earth's surface, constant atmospheric currents (the trade winds) will stabilize. Atmospheric upwelling is characterized by higher humidity caused by adiabatic phenomena that control air saturation. Regional atmospheric circulation is triggered by different heat capacity of land and sea-level. Changed position of circulating cells during seasons leads to seasonal flow changes (monsoons). Sea winds bring moisture that condenses in lifting flow over the coast. Therefore, windward slopes tend to be more humid and the climate of eastern and western coasts can be diametrically different.

Hedley and Ferrel cells interface runs between 15° and 35° latitude, where hot deserts with high evaporation form during climate minimum (when the Earth's axis is oblique to the ecliptics). Monsoon belts are few moving during seasons, limiting the input of precipitations into the area. Hadley/Ferrel downwelling zone moves to the poles and desert zone shifts to 35-40 during climate maximum (reduction of the axis tilt). The monsoon cycle is more efficient and humidity is rising in the zone between 10°-35°. Upwelling arms of both Ferrel and Polar cells shift to 70°, enabling the origin of non-glacial cycles (Miall, 1997). De Boer and Smith (1994) stressed the effectivity of precessional cycles at low latitudes, modulated by Earth's orbit eccentricity. They shift caloric equator and borders of climatic zones. Orbital changes affect relative length of seasons, winter and summer contrasts, and monsoon intensity in mid-latitudes. At high latitudes, the effect of changing obliquity is more evident.

Milankovitch major claim to fame was to demonstrate the phase difference on basis of laborious and lengthy time slices calculations (today they can be mastered relatively easy by standard computer). Calculation of orbital changes (based on interactions between sediment, climate and stimulated orbital insolation) are now combined with the geometry measuring cycles, sedimentological assays, mineralogy of clays, analyzing the C and O isotopes and spectrum of organic residues. Exceptionally well-preserved series of astronomical signals gave rise to a method known as "cyclostratigraphy" and build the model of the solar system dynamics in a continuous sequence called the "astronomical time scale" (Martinez et al., 2015).

The use of cyclostratigraphy and compilation of astronomical time scale unprecedently specified dating of geological boundaries, especially of the Cenozoic and Mesozoic era (from the existing uncertainty of ~ 0.5 My to ~ 40 to ~ 20,000 years). Neogene astronomical time scale has been prepared with an accuracy of 0.02 My. The resolution towards the Oligocene (prior to 30 My) decreased to 0.04 ka and Eocene - Paleocene strata (50-60 My ago) to 100,000 ka. So far, development of dating is limited by uncertainties related to the diffusion of the solar system (Hinnow and Ogg, 2007). Tolerance of the Mesozoic astronomical time scale is currently about 0.4 - 0.5 My, that is roughly equivalent to the accuracy of biostratigraphic method. Paleozoic cyclostratigraphy, over 250 My provides sufficient appropriate data, but relating astronomical time scale is hampered by the lack of astrodynamical model of this period, which is quite different (e.g., different duration of precession and obliquity). A development of settled astronomical time tends towards improved distinctiveness of the geological time scale at least an order of magnitude. As noted by Hinnow and Ogg (2007), the solution of detailed chronically thorny problems associated with lithospheric plate tectonics, global geochemical cycles, paleoclimate, sea level changes, or biotic processes depends on it.

References:

Adhémar, J. A. 1842. Révolutions de la mér déluges périodiques. *Carilian-Doeuvry et Dalmond: Bachelier, Paris*, 184 pp.

Agassiz, L. 1840. Études sur les glaciers. *Agassiz, Jent & Glassmann, Neuchâtel*, 345 pp.

Bradley, W.B. 1929. The varves and climates of the Green River epoch. *U.S.Geol Survey Prof. Paper*, 158, E, 87–110.

Copernicus, N. 1543. De revolutionibus orbium coelestium. *Johannes Petreius, Nuremberg*. 405 pp.

Croll, J. 1889. Stellar evolution and its relations to Geological Time. *New York, Appleton*. 136 pp.

De Boer, P. L. & Smith D. G. 1994. Orbital forcing and cyclic sequences. *International Association of Sedimentologists Special Publication*, 19, 1–14.

Emiliani, C. 1955. Pleistocene temperatures. *Journal of Geology*, 63, 6, 538–578.

Gilbert, G. K. 1895. Sedimentary measurement of geological time. *Journal of Geology*, 3, 121–127.

Hays, J. D., Imbrie, J. & Shackleton N. J. 1976. Variations of the Earth´s orbit: Pacemaker of the Ice Ages. *Science*, 194, 4270, 1121–1132.

Hinnov, L. A. & Ogg, J. G. 2007. Cyclostratigraphy and the astronomical time scale. *Stratigraphy*, 4, 2-3, 239–251.

Hutton, J. 1788. The Theory of the Earth, or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the Globe. *Transactions of the Royal Society of Edinburgh*, 1, 2, 209–304.

Kneževič, Z. 2010. Milutin Milankovič and the astronomical theory of climate changes. *Europhysics News*, 41, 3, 17–20.

Maclaren, Ch. (1842): The Glacial Theory of Professor Agassiz of Neuchậtel. *American Journal of Science*, 42, 346–365.

Martinez, M., De Conninck, J.-F., Pellenard, P., Reboulet, S., Company, M. & Riquier, L. 2013. Astrochronology of the Valanginian Stage from reference sections (Vocontian Basin, France) and palaeoenvironmental implications for the Weissert Event. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 376, 91–102.

Martinez, M., De Conninck, J.-F., Pellenard, P., Riquier, L., Company, M., Reboulet, S. & Moiroud, M. 2015. Astrochronology of the Valanginian - Hauterivian stages (Early Cretaceous): Chronological relationships between the Paraná - Etendeka large igneous province and the Weissert and Faraoni events. *Global and Planetary Change*, 131, 158–173.

Martinez M. & Dera G. 2015. Orbital pacing of C fluxes by a ~9-My eccentricity cycle during the Mesozoic. *PNAS*, 112, 41, 12 604–12 609.

Miall, A. D. 1997. The Geology of Stratigraphic Sequences. *Springier, Berlin.* 435 pp.

Michalík, J., Reháková, D., Kováč, M., Soták, J. & Baráth, I. 1999. Geológia stratigrafických sekvencií. Základy sekvenčnej stratigrafie. *VEDA, SAV Bratislava*, 233 pp.

Milankovič, M. 1941. Kanon der Erdebestrahlung und eine Anwendung auf das Eiszeitenproblem. *Royal Serbian Academy special publications, Section of Mathematical and Natural Sciences*, 132, 20, 1–633.

Penck, A. & Brückner, E. 1901. Die Alpen in Eiszeitalter. *Teuschnitz, Leipzig*. 1199 pp.

Sha. J., Olsen, P. E., Pan, Y., Xu, D., Wang, Y., Zhang, X., Yao, X. & Vajda, V. 2015. Triassic-Jurassic climate in continental high-latitude Asia was dominated by obliquity-packed variations (Junggar Basin, Urumqi, China). *PNAS*, 112, 12, 3 624–3 629.

Tang, D., Shi, X. & Jiang, G. 2014. Sunspot cycles recorded in Mesoproterozoic carbonate biolaminites. *Precambrian Research*, 248, 1–16.