Correlated variations and periodicity of global CO₂, biological mass extinctions and extra-terrestrial bolide impacts over the past 250 million years and possible geodynamical implications

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Earth’s history has been witness to recurrently alternating phases of catastrophic evolution and dominant tectonic deformations, contractions and extension of rifting and spreading leading to quasi-cyclic changes in sedimentary environment and various earth processes. Recent studies have shown quasi-periodicities of 32 ± 2 Million years (Myr) in various endogenic (geomagnetic reversals, magmatic events, mantle convection, various tectonic activities, climate change and biological extinctions) and exogenic (impact cratering) processes indicating a remarkable kinship. We present here time series analysis of the available CO₂ record over the past 250 Myr decoded from global CaCO₃ accumulation rates in sedimentary environment. The time series analysis reveals an intriguing evidence of a dominant periodicity of 33 ± 2 Myr which matches closely with a common «catastrophic periodicity» of 32 Myr identified in various terrestrial and extra-terrestrial records. We argue here for a common physical link among the periodic global CO₂ variations, mantle convection, geomagnetic reversals, volcanism, geotectonic cycles and enhanced cometary showers. We also suggest periodic variations in CO₂ as one of the possible terrestrial stimulators for the oscillating «greenhouse effect» and related climatic deterioration that result in quasi-periodic mass extinctions. Identical «catastrophic cycles» of endogenic and exogenic origin enhance the credence of their physical linkages and uphold the «concept of non-uniformitarianism» in earth’s processes.

Keywords: Periodicity, global CO₂, geodynamics

Introduction

The search for cycles in geological/geophysical records has a long distinguished tradition and honorable antiquity (Umbgrove, 1947). A phrase «Every thing on the earth operates in cycles» has recently been coined by Hazen and Trefil (1991) and enlisted among the 20 great ideas of science. Modern plate tectonic theory based on a conceptual model provides a common
quasi-cyclic link to all major geo-bio-ocean-atmospheric processes (Kearey and Vine, 1990; Caldeira and Rampino, 1991). Recognition of long term periodicity in various biogeochemical records is, therefore, essential in understanding exogenic and endogenic mechanisms. Recently long term cyclicity of the order of 33 ± 2 Myr has been postulated by many researchers in various processes of the earth (Fischer and Arthur, 1977; Seyfert and Sirkin, 1979; Negi and Tiwari, 1983; Raup and Sepkoski, 1984; Rampino and Stothers, 1984a, b; Pandey and Negi, 1987; Negi et al., 1990, 1996). Geological records of extra-terrestrial bolide impact cratering also have shown a comparable periodicity of 33 ± 3 Myr (Alvarez and Muller, 1984; Rampino and Stothers, 1988). In particular, Raup and Sepkoski (1984) analysed the marine mass extinction record of the last 250 Myr and suggested a periodicity of about 26 Myr. The same data were analysed by Rampino and Stothers (1984a) who suggested a periodicity of 30 ± 3 Myr. Confusion and negative criticism, however, came from the poor quality of the geological data and uncertainty in the geological time scale (Stigler and Wagner, 1987). As a result, evidence of cyclicity in geological records (Lutz, 1985) and in mass extinctions (whether 30 or 26 Myr) and impact cratering records (Grieve et al., 1985; Stigler and Wagner, 1987) have been questioned by some researchers. A comparison of geological time scale published in the last 10 years, however, shows considerable agreement among the dates with some uncertainty of about 2–7% (Rampino and Caldeira, 1993). Some independent analyses have also indicated large uncertainties in geological dates of stratigraphic turnover which in some cases may be simply unrealistic and misleading (Stothers, 1989).

Search for periodicity using improved geological time series and modern analytical techniques of time series analyses have revealed a clear pattern of a 32 ± 3 Myr periodicity in the terrestrial and extra-terrestrial impact cratering records. (Rampino and Caldeira, 1993; Stothers, 1986; Yabushita, 1990; Negi et al., 1990, 1996).

It is interesting to note that a 33 Myr periodicity in terrestrial record compares well with the best astronomical estimates of the half period of the solar system's vertical oscillation about the plane of the galaxy (time between one plane crossing and the next), which is approximately 33 ± 3 Myr (Rampino and Stothers, 1984). This indicates a possible extra terrestrial influence of sun's motions on the various earth's processes including biotic crises. Some researchers believe in non-cyclic biotic crises related to endogenic forcing such as volcanism, sea level changes and climate etc., (Officer and Drake, 1983). Several other researchers, however, observed that a periodicity of the order of 30 ± 3 Myr does exist (Raup and Sepkoski, 1986, 1988) in biological mass extinction record and may be related to the extra-terrestrial origin (impact cratering) (Rampino and Stothers, 1984a; Alvarez and Muller, 1984). This has, therefore, led to a considerable confusion with respect to (i) evidence of periodicity in the geological record and (ii) possible causes and effects of biological mass extinc-
tion. It is difficult to single out an independent possible cause for periodic biological crisis. It has become imperative, therefore, to discuss alternative geophysical evidences and ideas indicative of biological crises. The main goal of the present paper is (i) to examine evidence of periodicity in the available long term CO₂ record and (ii) to discuss its possible linkages with various terrestrial and extra-terrestrial phenomena as well as mass extinction, global CO₂ variation and climate changes during the past 260 Myr.

**The CO₂ data**

It is known that relative changes in the volume of carbonate rocks in sediments reflect changes in atmospheric CO₂ (Budyko and Ronov, 1979). A detailed compilation of such a record, based on a complete inventory of existing sediments on the platforms, geosynclines and slope and rise (pelagic sediments) has been presented by Hay (1985). The masses of CO₂ present as carbonate in other sedimentary rocks (clay, sands and evaporites) and carbon contents in pelagic sediments other than carbonate oozes is also included (Hay, 1985). The CO₂ record also comprises much information from the continental margin and open ocean. In addition to these data most recently published CO₂ data are also compared for the past 100 Myr. The anomalous values of CO₂ at 81, 86, 93 Myr, 59–60 Myr and 15–20 Myr (Compton and Mallinson, 1996) are taken into consideration for our present analysis. We note here however, that there are some caveats with the geological records which must be spelled out prior to any quantitative analysis. The anomalous atmospheric CO₂ levels are difficult to identify in the geological record due to following reasons. First, enhanced degassing of CO₂ is countered by increase in weathering or organic carbon burial and secondly increases in chemical weathering show up in the net global carbonate burial flux. Here, the problem is two fold. First we have to have a reasonable estimate of both the carbonate and organic carbon net burial fluxes through time. But unfortunately these fluxes are very difficult to quantify through geologic time because of preservation bias (younger rocks better known than older rocks) and summing up all of the deposits both pelagic, margin and terrestrial. These are some of the problems which limit the interpretation of CO₂ record. Nevertheless, we feel confident that available episodic CO₂ data of Hay (1985) might serve as possible guide to understand CO₂ variation in relation to other similar geological episodic and tectonic records. Global CO₂ accumulation rates data are presented in Table 2, which reveal high CO₂ accumulation rates during the Pliocene 2–5 Myr, Eocene 37–58 Myr, upper to mid-Cretaceous 66–98 Myr, upper Jurassic 144–163 Myr, mid Triassic 230–249 Myr, and early Permian 258–286 Myr. The available total CO₂ record entails enough precision homogeneity and completeness for the time series analysis. Long term global CO₂ variation, one of the major climatic controllers on planet
earth, has been neglected in empirical studies. A meaningful quantitative analysis of the available data may thus shed some light on its evolution and understanding of its linkage to various other related phenomena.

**Impact cratering, cyclic CO₂ variations and biological mass extinctions: A geodynamic perspective**

Long term global CO₂ variation has been linked to the various processes of the earth's interior (e.g., lithospheric dynamics, mantle rheology etc.). The ocean-atmosphere carbon mass has been recycled on hundred thousand year time scales. Enhancement of CO₂ is mainly due to faster spreading rates due to broadening of the oceanic ridge system. Significant changes in the pattern of ocean floor spreading can be inferred from the studies of marine magnetic anomaly pattern, age determination of ocean crust and bend in linear island segment chain. The dates of recognised major discontinuities in global sea floor spreading and major orogenic events are given by Rampino and Caldeira (1993 and references therein). In order to tie the episodic enhancement dates of CO₂ variations with already well known existing geodynamic dates, we present here a comparison of well known dates of the plate motions and sea floor spreading (Table 1). It is remarkable to note that almost every episode of initiation of CO₂ events seem to be associated with distinct kinematic; events of plate motions. Certain coincidences are rather compelling; e.g. mid-Cretaceous and late Jurassic sea floor spreading and associated volcanism, (Arthur et al., 1985). During these periods worldwide sea floor spreading, rifting and extensive plate reorientation started. Thus the comparison of these anomalous CO₂ dates with major tectonic events (Table 1) shows that the CO₂ record contain an unbiased and distinct history and have been recognised as times of high CO₂ turn over.

Table 2 shows the dates of major episodic changes and time domain correlation of high CO₂ (initiation dates) with mass extinction events, tectonic events, bolide impact cratering and time of galactic plane crossing of solar system. The events are taken from Rampino and Caldeira (1993) and Sepkoski (1989). The extinction data include all peaks in the percentage genera extinction rate which are based on all 70, 500 genera in latest data set (Rampino and Caldeira, 1993). Rampino and Stothers (1988) have presented updated data of initiation of times of eleven continental flood basalts which represent the largest outpourings of mafic magma. These data are absolute ages based on more than 900 published radiometric and isotopic age determination. According to these workers, eruption of most of the basalts takes place within 2–3 years at most indicating catastrophe recurrence of events.

Comparison of these data shows a remarkable correlation, although one-to-one correspondence of these events in time domain may not be expected.
probably due to the fact that different geological processes exhibit different relaxation times. The possibility, however, might indicate that various earth’s processes (e. g., volcanism, sea level changes, climate, extra-terrestrial impact cratering and atmospheric processes) form a complex interactive cyclic loop with a certain characteristic time scale. It is prudent, therefore, to present these data with cycle number.

In a reprojection of mass extinctions, orogenic events, sea floor spreading separately and volcanic episodes and CO₂ dates with age and cycle numbers, we find an interesting correlation in Figure 1 (a, b, c, d). The dates of impact cratering (bolide impact) of extra-terrestrial origin on the surface of the earth and galactic plane crossings time also clearly show a remarkable coincidence with the distribution of high CO₂ accumulation rates by age and cycle num-
Table 2. Time domain correlation of CO₂ episodes with mass extinction, impact cratering and galactic disc crossing time

<table>
<thead>
<tr>
<th>Geological age⁴</th>
<th>Geological disc crossing⁶</th>
<th>Impact cratering⁶</th>
<th>Enhanced CO₂ rate⁷</th>
<th>Orogenic events¹⁵</th>
<th>Mass extinctions⁵</th>
<th>Sea floor spreading⁴</th>
<th>Flood basalt⁴</th>
<th>Cycle No.</th>
</tr>
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<tr>
<td>Mid-Miocene</td>
<td>0</td>
<td>7</td>
<td>5</td>
<td>0.6, 2.5, 4.5, 12.5</td>
<td>11</td>
<td>2, 10, 17</td>
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<td>0</td>
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<td>38</td>
<td>37</td>
<td>25, 40</td>
<td>36.6</td>
<td>40, 53</td>
<td>35</td>
<td>1</td>
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<td>78</td>
<td>66</td>
<td>65</td>
<td>66</td>
<td>63, 77</td>
<td>62, 66</td>
<td>2</td>
</tr>
<tr>
<td>Early Cretaceous</td>
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<td>98</td>
<td>93</td>
<td>80, 87</td>
<td>91</td>
<td>94, 112</td>
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<td>144</td>
<td>148</td>
<td>130, 135</td>
<td>4</td>
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<td>Bajocian</td>
<td>166</td>
<td>160</td>
<td>–</td>
<td>–</td>
<td>176</td>
<td>–</td>
<td>170</td>
<td>5</td>
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<tr>
<td>Pleinsbachian</td>
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<td>184</td>
<td>168</td>
<td>–</td>
<td>193</td>
<td>–</td>
<td>190, 200</td>
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<td>214</td>
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<td>220</td>
<td>217</td>
<td>–</td>
<td>–</td>
<td>7</td>
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<tr>
<td>Dzhulfian</td>
<td>259</td>
<td>–</td>
<td>258</td>
<td>250</td>
<td>245</td>
<td>–</td>
<td>–</td>
<td>8</td>
</tr>
</tbody>
</table>

¹⁴Raup and Sepkoski (1984)
¹⁵Rampino and Stothers (1984a)
¹⁷Rampino and Caldeira (1993)
Figure 1. Correlation of global CO₂ data (×) with (a) mass extinction, (b) orogenic events, (c) volcanic episodes and (d) ocean floor spreading over the past 250 Myr. The episodic ages are plotted with respect to cycle numbers.

Figure 2. Correlation of global CO₂ (×) over the past 250 Myr with the dates of (a) galactic plane crossings and (b) impact cratering.
ber for the past 250 Myr (Figure 2a, b). Interestingly, Figure 1 a, b shows an almost obvious average cycle of about 30 ± 2 Myr for at least five cycles. We further examine the stability and significance of 30 Myr cycle in CO2 record using appropriate time series analysis technique.

**Time series analysis**

Deciphering hidden cyclicity patterns from the raw geological/geophysical data by visual inspection may not be appropriate for various reasons including dating errors and sampling problems. Statistical analysis of ages therefore is an objective approach for quantification of cyclic patterns in geological records (Rampino and Caldeira, 1993). In order to have more confidence in periodicity in CO2 time series record, we performed a quantitative analysis of initiation times of anomalously enhanced CO2 dates (Table 2). As the available CO2 data are episodic in nature, it does not permit us to treat them by using traditional methods of spectral analyses. We have, therefore, chosen an alternative method based on a non-parametric approach which could be applied to identify periodicity from such episodic data series (Stothers, 1979). Accordingly, a non-parametric method of time series analysis has been specially designed by Rampino and Stothers for such records in which just the dates (and not the amplitudes) of the events are recorded and noise is a problem. In this method, the observed dates \( t_i \) (\( i = 1, 2, 3, \ldots \)) are fitted to a linear formula of the type \( t = t_0 + np \) (where \( p \) is trial period, \( t \) is trial phase for most recent epoch and \( n \) is an integer). The resulting sums of the squares of the residuals are minimized at each trial period to obtain a best fit for selected trial period as computed residual index \( \sigma = \sigma_c / P \) where \( \sigma_c = [\sum (N^2 - 1)/12n^2]^{1/2} \). The result is displayed in Figure 3 which apparently reveals a 33 ± 3 Myr periodicity. Following Stothers (1986), the statistical reliability test was performed by generating a number of random artificial time series from the dates selected within time interval 0–260 Myr. The comparison of spectrum of the residual index for each time series with original spectra, reveal that peak at 33 Myr is significant at >90% confidence level.

Raup and Sepkoski (1984) have also developed a similar method in which they search for the arithmetic mean of the residuals that is closest to zero. Lutz (1985) made a circular transformation to obtain phases of the observed data, the dispersion of which is then minimized by performing trigonometric summations as in Fourier analysis. Lutz (1985) variation method allows a correction to be made for unique weighting of the dates which considerably biases time series analysis (Stothers, 1986). One of the advantages of the technique used here is that it tolerates well a moderate amount of irregularity in the periodicity as well as some noise in the time series dates and random gaps (Stothers, 1979). The method used here to analyse CO2 data therefore seems appropriate and unbiased.
Discussion of the results

The foregoing analysis reveals possible evidence of the $33 \pm 2$ Myr periodicity in the global CO$_2$ variations for the past 260 Myr which is similar to the periodicity of $31 \pm 2$ Myr in several other terrestrial/extra-terrestrial phenomena. A conceptual unifying model of pulsation tectonics proposed by Sheridan (1983, 1987) suggest possible relations among sea floor spreading, out-breaks of hotspots (flood basalts, rifting, orogeny etc.), sea level changes, composition of ocean chemistry, and atmospheric processes (including atmospheric CO$_2$) through perturbation of carbon silicate cycle. Results based on various types of data analysis fully agree with Sheridan's cyclic model. The driving mechanism for major tectonic oscillations might be the changing configuration of earth's plate or internal core mantle dynamic processes. This also might have affected the geomagnetic field as well (Courtillot and Besse, 1987). Loper and McCarteney (1986) provided evidence for a 30 Myr periodicity in mantle convection due to instability of the thermal boundary layer (D'') at the base of the mantle. They have also provided evidence for periodic thickening and thinning of D'' layer which eventually affect the activity of the core processes and hence the periodic geomagnetic reversals. Recent investigations have suggested the possible evidence of periodicity in the geomagnetic reversal record. Negi and Tiwari (1983) constructed a telegraphic signal model of observed percentage of normal and reversed polarity during different Phanerozoic time intervals. Walsh spectroscopy of telegraphic sig-
nal has revealed several significant periodicities notably around 285 Myr and 32–34 Myr. Interestingly, 285 Myr and 32–34 Myr cycles nicely match with the «cosmic year term» and a time constant of vertical oscillations of the solar system at the plane of the galaxy. Raup (1985) used the dates of individual reversals for the past 160 Myr to propose a 30 Myr periodicity in frequency of geomagnetic reversals. An evidence of 15 Myr periodicity has also been suggested by Mazaud et al. (1983) which may possibly be the harmonics of basic 30 Myr cycle. Raup (1985) has retracted his original claim following criticism by Lutz (1985). However, Stothers (1986) presented a much fuller analysis of the reversal record and showed that a statistically significant period of 30 Myr does formally exist. Like Stothers (1986), we also strongly believe that the available data and their appropriate analysis do suggest a common cycle of about 33 ± 2 Myr. Thus the major tectonic processes, driven by thermal structures and convective pattern of the mantle could be the possible cause of periodic fluctuations in various related earth processes.

Alternatively, a likely possible link involving a combination of exogenic and endogenic forcing has been suggested by Sepkoski (1986). Accordingly an internally generated 30 Myr period in the earth’s tectonism and climate possibly arised due to random extra terrestrial impacts that sometimes greatly amplify the quasi periodic oscillation in environment (Rampino and Caldeira, 1993). Time series analysis of terrestrial impact cratering (Rampino and Stothers, 1984a; Alvarez and Muller, 1984; Yabusita, 1991) suggests a possible 30 Myr periodicity. The significance of detected periodicity in cratering have been questioned by Grieve et al. (1987) although the most recent work maintain that periodicity may be robust even under stringent criteria (Rampino and Caldeira, 1993). Melosh (1989) has provided a more quantitative measure and convincing argument to the effect of impact on the earth surface and its possible consequences on geological processes. Accordingly the planetesimal impact represents the most energetic events that can perturb the earth. As also mentioned by Rampino and Caldeira (1993), an ~10 km diameter impactor, which are estimated to strike the earth at rate of one every 20–100 Myr (Stothers and Rampino, 1990; Barlow, 1990), provides a total of at least 10^24 J with 0.01 % or 10^20 J going instantaneously into seismic energy (eventually dissipated as heat). According to these workers, this is 100 times greater than the yearly release of terrestrial seismic energy (10^18 J) and the rate of energy input (10^20 J s^{-1}) is 10^7 times the rate of global heat flow. The impact seismic energy is equivalent to a magnitude of 11–12 earthquakes with oscillating ground motion of hundreds of meters even further than 1000 km from the impact site (Melosh, 1989; Rampino and Caldeira, 1993).

A plausible explanation for cometary impacts on the earth’s surface has been suggested by Rampino and Stothers (1984), Melosh (1989). Accordingly, the solar system bobs up and down through the Milky way galactic disc. Ter-
restrial upheaval including biotic crises may have arisen as a result of collision (or close encounters) of the solar system with intermediate-sized to large-sized interstellar clouds of gas and dust which are sufficiently concentrated towards the galactic plane. A nearby interstellar cloud would gravitationally perturb the solar system's family of comets (Oort cloud) and thereby increase the flux of comets and comets derived bolides near the earth leading to large body impacts. Impact cratering (>10 km diameter on the surface of the earth) may have perturbed the mantle flow including several other consequences such as fracturing the crust and generating vigorous mantle plume activity (Rampino, 1987). Increased outgassing of mantle CO₂ during sea floor spreading, high tectonic activity, sea level changes and intense volcanism may have profoundly raised the level of atmospheric CO₂ causing the periodic enhanced «greenhouse» warming leading to global climate changes and mass extinction (Campsie et al., 1984; Mclean, 1985; Arthur et al., 1985). Hence, the high CO₂ level associated with high rates of sea floor spreading may directly be related to the mantle convection induced by impact cratering, and hence to the rates of subduction and subduction related volcanism and magma generation (Berner et al., 1983; Arthur et al., 1985). Similarly, the observed long term sea level changes may be attributed to the changes in sea floor spreading rates and the ridge volume (Hays and Pitman, 1973; Morner, 1980). There is evidence of a 32 ± 2 Myr cycle in paleo-temperature possibly due to CO₂ variation (Dorman, 1968), sea level changes record (Negi et al., 1990), climate change (Shackleton and Imbrie, 1990) and in secular variation of dolomite abundance (Negi et al., 1996). From Table 2, however, one can clearly visualize mismatching dates of episodes of the various pro-

Figure 4. A simplified geo-galactic model relationship of terrestrial catastrophism and the Sun's motion in the galaxy.
cesses which might lead to considerable phase lags. We note that bobbing the solar system up and down through the Milky way disc would be a very much hit or miss phenomena. The amplitude of the perturbation would also vary according to the size of impacts. In addition to this one would expect a time lag between cause and effect for many of these events. For instance, degassing of CO$_2$ will depend on global. rating of metamorphism, subduction volcanism etc. and yet many of these changes will spread over million years after the impact events. We mention that because it is not prudent to speculate over the issues of time lags due to errors involved in dating of the geological records. Our data do not exactly constrain the causes rather it provides a unified view of cyclicity in geological records. Impact induced changes of terrestrial processes, although highly debated at this stage, seems to be revolutionary for future studies. Figure 4 shows a conceptual model of the proposed chain.

Conclusions

(i) Time series analysis of available anomalous CO$_2$ dates for the last 260 Myr reveals a dominant periodicity of $33 \pm 2$ Myr. In view of obvious links between mass extinction cycle, CO$_2$, climate and sea level changes, it may be suggested that these processes may be governed by a common time constant of $30 \pm 2$ Myr. Periodic CO$_2$ changes seem to be one of the main endogenic stimulators, through climate change, of biotic extinction.

(ii) Matching quasi-periodicity of CO$_2$ variations and various other earth’s processes and bolide impact cratering with periodicity of galactic vertical motion of the solar system enhances credence of endogenic and exogenic links and provide a new dimension for the understanding of the geo-biochemical cycles on earth in a framework of the plate tectonic paradigm.

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Korelacijs između periodičnosti promjena globalnog CO₂, masovnih izumiranja vrsta i udara izvanzemaljskih bolida tijekom proteklih 250 milijuna godina s mogućim geodinamičkim posljedicama

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U Zemljinoj povijesti izmjenjivale su se faze evolucije kao posljedica prirodnih katastrofa s dominantno tektonskim deformacijama, kontrakcijama i širenjima, što je dovelo do pojave kvazi-periodičkih promjena u sedimentima, kao i kod mnogih sa Zemljom povezanih procesa. Nedavne studije ukazale su na kvaziperiodičnost od 32 ± 2 milijuna godina pri raznim endogenim (geomagnetske izmjene polova, vulkanizam, konvekcija u plašt, tektonska aktivnost, klimatske promjene i izumiranja vrsta) i egzogenim (udarni krateri) procesima, sa zamjetnim sličnostima. Prikazat ćemo analizu vremenskih nizova dostupnih podataka o količini CO₂ tijekom proteklih 250 milijuna godina, o čemu je zaključeno na temelju globalne akumulacije CaCO₃ u sedimentima. Analiza otkriva intrigantnu periodičnost od 33 ± 2 milijuna godina koja je evidentirana u raznim nizovima zemaljskog i izvanzemaljskog podrijetla. Predlažemo zajedničku fizikalnu vezu između globalne varijacije količine CO₂, konvekcije u plaštu, promjena geomagnetih polova, vulkanizma, geotektonskih ciklusa i pojačanih meteoriskih rojeva. Također predlažemo mogućnost da je periodička varijacija količine CO₂ jedan od mogućih Zemaljskih stimulatora promjenljivosti »efekta staklenika« i s time povezanog pogoršanja klime koje dovodi do masovnog izumiranja vrsta. Identični »ciklusi katastrofa« endogenog i egzogenog podrijetla dokaz su više u prilog njihovoj fizikalnoj povezanosti i u skladu s konceptom neuniformnosti pri procesima na Zemlji.

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