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How long will the “precession epoch” last in terms of Pleistocene glacial cycles?

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[1] Paleoclimate orbital theory, also known as astronomical, or Milankovitch theory is in common use to explain global climate changes in Pleistocene time, mainly glacial-interglacial cycles. However, there are well-known contradictions between this theory and empirical data that were intensively studied by a large number of scientists during last 30 years. Nevertheless, there has not been any important progress in resolution of these contradictions yet. This paper deals with a new approach to the research of problems relevant to the orbital theory. It is based on critical analysis of orbital theory history development. Main drawbacks of the recent version of the astronomical theory of paleoclimate and certain recommendations how to eliminate them are given. A great attention is given to the climatic influence of the Earth’s feedbacks and the Earth’s total annual insolation variations. *INDEX TERMS:* 0429 Biogeosciences: Climate dynamics; 0473 Biogeosciences: Paleoclimatology and paleoceanography; 1626 Global Change: Global climate models; 4934 Paleoceanography: Insolation forcing; *KEYWORDS:* Milankovitch theory, paleoclimate, annual insolation variations, Pleistocene glacial terminations.

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1. Introduction

[2] Several papers, published during the last six years [*Elkibbi and Rial,* 2001; *Huybers and Wunsch,* 2005; *Loutre et al.,* 2004; *Paillard,* 2001; *Raymo and Nisancioglu,* 2003], from my point of view, show the beginning of new stage in orbital (astronomical, Milankovitch) paleoclimate theory development. This new stage is related to M. Milankovitch theory reappraisal and could be characterized with D. Paillard words [*Paillard,* 2001, p. 343]: “The classical Milankovitch theory needs to be revised to account for the traditional peculiarities of the records, like the 100-kyr cyclicity and the stage 11 problem”. The impact of the Earth axial inclination on Pleistocene climate changes has received much attention from the authors of mentioned above papers. Effects connected with obliquity insolation variation and its gradient between high and low latitudes are considered to be the most important, that could manage climate during the period from 2.5 to 1 million years ago [*Raymo and Nisancioglu,* 2003] and might well accelerate Pleistocene glacial terminations [Huybers and Wunssch, 2005].

[3] However, development of paleoclimate orbital theory (and Milankovitch theory revision) could be improved applying another approach. The approach implied is based on the history of theory development critical analysis. Based on this approach anyone can at once give an answer to the question stated in the *Loutre et al.* [2004]: “Does mean annual insolation have the potential to change the climate?”. In my opinion, the answer should be: “Yes, it does”.

[4] Such an answer is quite obvious in case of solar constant change. In this case the increase of Earth total annual radiation will lead to global warming and its decrease – to global cooling. (I guess that Simpson hypothesis [*Simpson,* 1938], assuming that a minor solar radiation increase could result in glaciation, hasn’t been properly based). For the orbitally-driven insolation variations the answer to the question stated should also be positive.

[5] Eccentricity is known from the early 19th century to be the only orbital parameter changing the Earth’s total average annual insolation. Assuming the Earth surface is a sphere the Earth’s total insolation is not changed, but latitudinally redistributed by the axial inclination angle ε variations. Angle ε decrease results in average annual insolation decrease at high latitudes and insolation increase at low latitudes. ε rise leads to opposite result. Hence, during inclination angle variations, average annual insolation of high and low latitudes changes in opposite phases (phase inversion occurs between 44° and 43° latitudes of both hemispheres). Besides, relative annual insolation change of high latitudes is higher than that of low latitudes.

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[6] *J. Croll* [1875] was the first to propose a proper mechanism of the Earth axis inclination variations climatic influence. He was also the first to account for the change of the total annual insolation along with the forcing of snow and ice albedo at high latitudes. Croll concluded that inclination angle ε decrease would lead to global cooling, whereas ε enhancement would result in warming, glacier melting at high latitudes in both hemispheres and ocean level rise. Milankovitch used the same mechanism in 1930 [*Milankovitch,* 1930]. Thus we may conclude that J. Croll got the answer to the question stated in paper [*Loutre et al.,* 2004] more than 130 years ago.

[7] Consequently, the important problem of average annual insolation climatic influence has got a long history which one should know and understand. Another reason is that the knowledge obtained leads to more fundamental understanding of orbital theory problems. Below is given the brief historical review of orbital theory development.

2. Critics of the Orbital Hypothesis and Solution Proposed by Croll of the Zero Equality Problem of Average Annual Precession Insolation

[8] The first version of orbital theory (hypothesis) proposed by *Adhémar* [1842] assumes that glaciations in both hemispheres were related to precession-controlled long cold winters. This assumption was criticized by British astronomer J. Herschel and German naturalist A. von Humboldt [*Croll,* 1875; *Imbrie and Imbrie,* 1986]. They claimed the average annual insolation is not changed by precession variations at any latitude, as winter insolation decrease is compensated by summer insolation increase and vice versa, also at any latitude. Therefore a long cold winter is followed by a short hot summer in one hemisphere and simultaneously a long cool summer is followed by a short mild winter in another one. Hence, annual average heating (and temperature) do not change with precession variations.

[9] Thus, to explain the glaciations existence basing on orbital theory, it is essential to find a complementary factor that gives rise to appearance and retaining of ice sheets during millennia, vast spaces of high and middle latitudes to be covered despite inverse semi-annual precession insolation contrasts. J. Croll has found such a factor and, from my point of view, this discovery is an outstanding achievement of theoretical paleoclimatology.

[10] J. Croll realized that the direct influence of insolation variations on climate is slight, since the eccentricity-driven insolation changes are very small and average annual changes of Earth's total solar radiation having been connected with two other orbital elements are virtually null (are "compensated"). He wrote [*Croll,* 1875 p. 13]: "There is, however, one effect that was not regarded as compensated. The total amount of heat received by the earth is inversely proportional to the minor axis of its orbit; and it follows therefore, that the greater the eccentricity, the greater is the total amount of heat received by the earth. On this account it was concluded that an increase of eccentricity would tend to a certain extent to produce a warmer climate. All those conclusions to which I refer arrived at by astronomers, are perfectly legitimate so far as the direct effects of the eccentricity are concerned, and it was quite natural, and, in fact, proper to conclude that there was nothing in the mere increase of eccentricity that could produce a glacial epoch. How unnatural would it have been to have concluded that an increase in the quantity of heat received from the sun should lower the temperature, and cover the country with snow and ice! *Neither would excessively cold winters, followed by excessively hot summers, produce a glacial epoch. To assert, therefore, that the purely astronomical causes to produce such an effect would be simply absurd...* (emphasized by me – V. B.). The important fact, however, was overlooked that, although the glacial epoch could not result directly from an increase of eccentricity, it might nevertheless do so indirectly. Although an increase of eccentricity could have no direct tendency to lower the temperature and cover our country with ice, yet it might bring into operation physical agents which would produce this effect".

[11] Croll was the first to introduce Earth positive feedbacks that enhance the insolation variations climatic influence as the physical agents. The first one is related to snow and ice cover albedo, the second one – to ocean current of the Atlantics. The glaciation mechanism was the following. During notably cold and long winters in one hemisphere, when the eccentricity was especially high and winter solstice was far from the Sun, next to the aphelion, the snow cover of this hemisphere grew significantly. The joint effect of cold winters, growing snow cover and positive albedo feedback resulted in the hemisphere annual temperature progressive decrease, despite the hot summers were followed by long cold winters. Temperature decrease in high latitudes increased the temperature gradient between pole and equator, enhanced the trade winds that in turn changed the water currents of the Atlantics. The latter should have resulted in further hemisphere cooling up to glacial conditions. Another hemisphere witnessed the onset of interglacial.

[12] Thus, according to Croll glaciations occur during the periods of the extremely high eccentricity values in one or another hemisphere, when precession-determined distance between Sun and Earth in winter of any hemisphere becomes very great. Using Le Verrier equations Croll calculated Earth orbit eccentricity changes for 3 million years to the past and 1 million years to the future. According to these calculations notably high eccentricity values correlate with time intervals of 980–720 kyr and 240–80 kyr. These were time intervals which Croll attributed to glaciations. The latest glaciation should have terminated 80 thousand years ago. Hence, it was Croll rather than Milankovitch (as sometimes several authors write) who was the first to calculate orbital elements to assess the time of paleoclimatic events.

[13] However, Croll's theory did not correlate with empirical data. It was evidenced that the last glaciation finished not 80, but approximately 10 thousand years ago. Besides, the coincidence of glaciations in northern and southern hemispheres has been shown. Therefore Croll's theory was rejected in the end of 19th century.

3. Milankovitch Theory, Its Main Contradictions and Drawbacks

[14] M. Milankovitch was the second scientist after J. Croll who contributed greatly to orbital theory development. Milankovitch theory differs in mathematically strict calculations of orbitally-caused variations of insolation at the upper atmosphere boundary for the last million years. He has accounted for the change in time of all the three orbital elements, whereas in the lifetime of Croll there were no reliable calculations concerning the change of obliquity.

[15] Milankovitch dealt with the zero values of average annual global insolation variations related to precession and Earth axis inclination problem alternatively than Croll did 50 years ago. Milankovitch considered only semi-annual insolation variations for certain latitudes. Besides, Milankovitch, contrary to Croll, according to Köppen advice, believed that glaciation is favoured by long cool summers rather than by long cold winters. To interpret the northern hemisphere glaciation he used the insolation diagram calculated for summer thermal half year at 65°N [*Milankovitch,* 1930]. Milankovitch regarded the deepest insolation diagram minima as northern hemisphere glaciations. Earth axis inclination variations and precession were nearly of the same contribution in that curve. Milankovitch as Croll 50 years ago ignored direct insolation changes related to eccentricity variations. Consequently, climatic cycles according to Milankovitch theory should mainly amount to 41 kyr due to Earth axis inclination and 19 kyr due to precession.

[16] Deep water oxygen-isotope data are known to have confirmed the Adhémar-Croll hypothesis on relation between climatic changes and orbitally-caused insolation variations. All the orbital periods have been shown to be reflected in paleoclimatic records. Furthermore, phase consistency between insolation effect and climatic response was found in the orbital frequency band. However, the same data showed significant contradictions between Milankovitch theory and empirical data [*Bassinot et al.,* 1994; *Berger,* 1999; *Elkibbi and Rial,* 2001; *Hays et al.,* 1976; *Imbrie et al.,* 1993; *Paillard,* 2001, and others]. Major contradictions of Milankovitch theory are the following [*Berger,* 1999; *Bol'shakov,* 2001, 2003a, 2003c; *Elkibbi and Rial,* 2001; *Hays et al.,* 1976; *Imbrie et al.,* 1993; *Paillard,* 2001].

[17] (1) Climatic cyclicity of the Brunhes chron is primarily determined by the 100-kyr periodicity, assigned to eccentricity variations, whose direct influence has not been discussed in Milankovitch theory.

[18] (2) A number of glaciations and their time do significantly differ from similar glaciation parameters in the Milankovitch insolation diagram, plotted for summer insolation at 65°N.

[19] (3) According to empirical data, glacial events fall on eccentricity minima, whereas in Milankovitch theory they (the deepest minima on insolation diagram) mainly fall on the eccentricity maxima.

[20] (4) In his theory Milankovitch states that temperature variations are similar to his calculations of semi-annual insolation changes (the so-called linear mechanism of insolation variation amplification). Since insolation change for low and moderate latitudes is mostly precession-determined, summer and winter insolation change as well as summer and winter temperature are in opposite phases even at 55°N and 65°N. Thus by Milankovitch summer temperature falls, while winter temperature rises in the time of glaciations. Whereas during interglacials summer temperature rises, while winter temperature falls [*Milankovitch,* 1930, diagram 4]. However, as is well known nowadays, summer and winter temperatures changed in identical phases during Pleistocene glaciations and interglacials. [*Kandiano and Bauch,* 2003; *Ruddiman and McIntyre,* 1981].

[21] (5) Global climate changes are synchronous in both hemispheres (at least for last glaciation maximum and Holocene optimum). Whereas insolation curves that Milankovitch calculated for 65°N and 65°S latitudes are shifted for no less than 5 thousand years in determination of temporary insolation minima and maxima position corresponding with this climatic event.

[22] (6) About a million years ago the main climatic periodicity changed from 41 kyr to 100 kyr. That doesn't comply with the Milankovitch theory as variations of orbital elements didn't change significantly at that time.

[23] Logically, the theory contradicting empirical data is incorrect. Thus, Milankovitch theory should be rejected, as it happened for the first time 50 years ago with this theory and nearly 100 years ago with Croll's theory [*Imbrie and Imbrie,* 1986; *Milankovitch,* 1930]. However, our predecessors turned to be more consistent than our contemporaries in 80s of 20th century, who started to "modernize" Milankovitch theory. The next important step in modernization was to use monthly or daily summer insolation at 65°N [*Berger,* 1980; *Berger and Loutre,* 1991], instead of semi-annual insolation used by Milankovitch. Such a modernization gave rise to a new conflict between theory and empirical data – an inconsistency between the maximal amplitude of insolation forcing precession harmonic (monthly or diurnal insolation variations at 65°N) and minimal amplitude of δ^{18}O climatic record 23-thousand years harmonic (Figures 1, 2). (Hence, it is sort of 100-kyr period in precession band problem mirror image [*Bol'shakov,* 2003c]).

[24] In the end of year 2006 the paper titled "In defence of Milankovitch" was published [*Roe,* 2006]. It would be better to call it "In defence of Milankovitch theory", because Milankovitch died in 1958. In his article Roe points out: "...progress has been impeded by the lack of a well-formulated, specific, and generally-accepted hypothesis. The term "Milankovitch hypothesis" is used in a variety of ways, ranging from the simple expectation that one ought to see orbital frequencies in time series of paleoclimate proxies, to the implication that all climate variability with time scales between 10^3 to 10^6 yr is fundamentally driven by orbital variations. Somewhere in the middle of this are the more vague statements found in some form in many textbooks, that orbital variations are the cause, or pacemarker, of the Pleistocene ice ages. Phrases like Milankovitch curves, Milankovitch insolation, Milankovitch frequencies, Milankovitch forcing, and Milankovitch cycles pervade the literature, adding to the somewhat nebulous picture".

[25] One can mainly agree with the above statement. In fact, the right wording of Milankovitch theory is for some

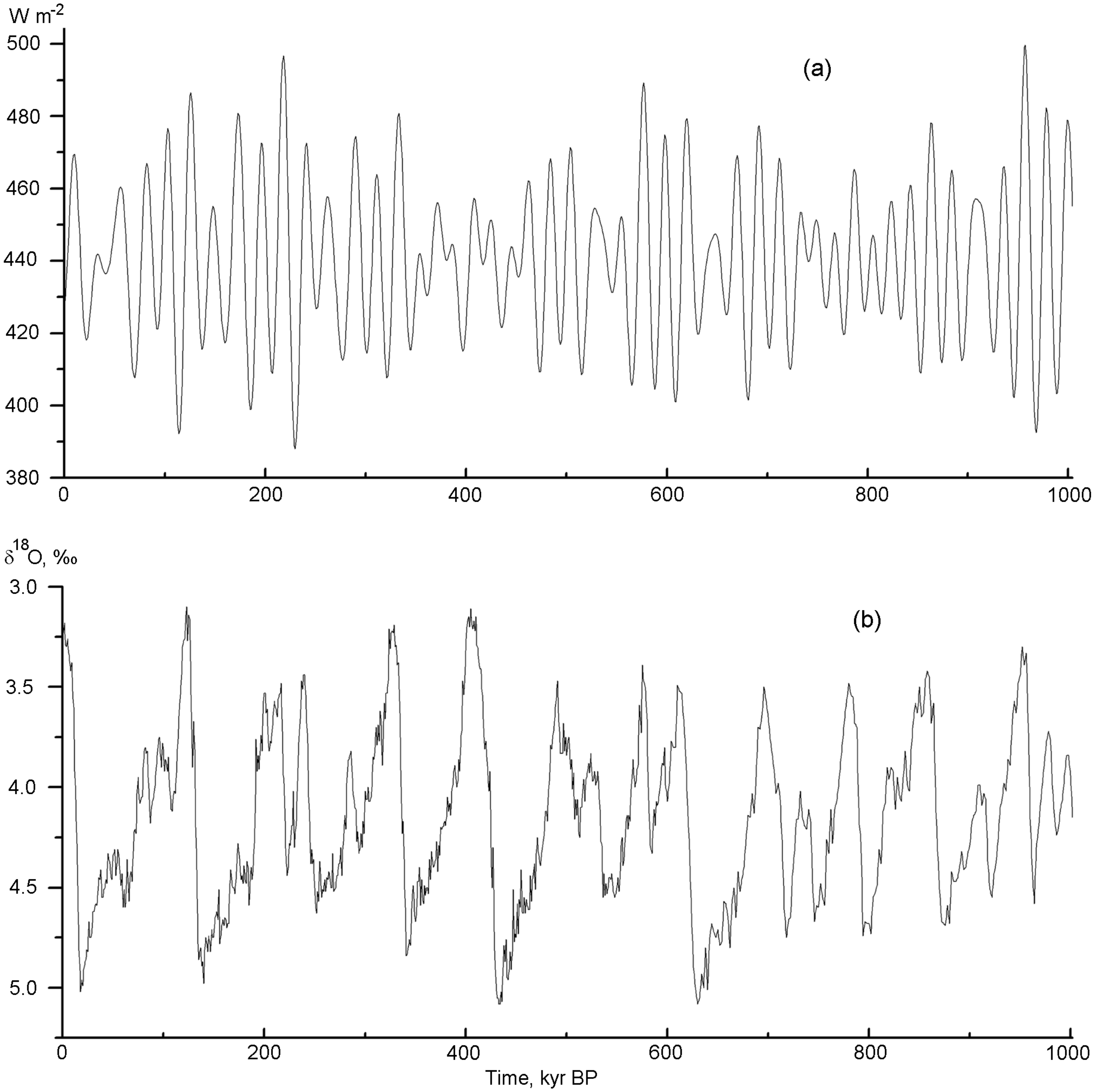

Figure 1. a – the change of July insolation at 65°N for the last million years (after [*Berger and Loutre,* 1991]), b – compound oxygen-isotope record LR04 for the time interval 0 to 1 million years (after [*Lisiecki and Raymo,* 2005].

reason a knotty problem. For example, in the introduction to the International conference “Milankovitch and climate” (1984) collected papers, signed by its well-known editors A. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman, Milankovitch theory is defined as follows: “The essence of the Milankovitch theory is that the major fluctuations in global climate associated with the ice-age cycle are caused by variations in the pattern of incoming solar radiation – variations that are, in turn, caused by slow changes in the geometry of the earth’s orbit that occur in response to predictable changes in the gravitational field experienced by the Earth”. Another example is the beginning of *Clemens and Tiedemann* [1997] paper: “Milankovitch theory – that climate is controlled by variations in the Earth’s orbital parameters – has gained wide acceptance...”. However, these definitions describe not a particular Milankovitch theory, but a more general orbital hypothesis that J. Adhémar, J. Croll and other scientists used as a basis for the development

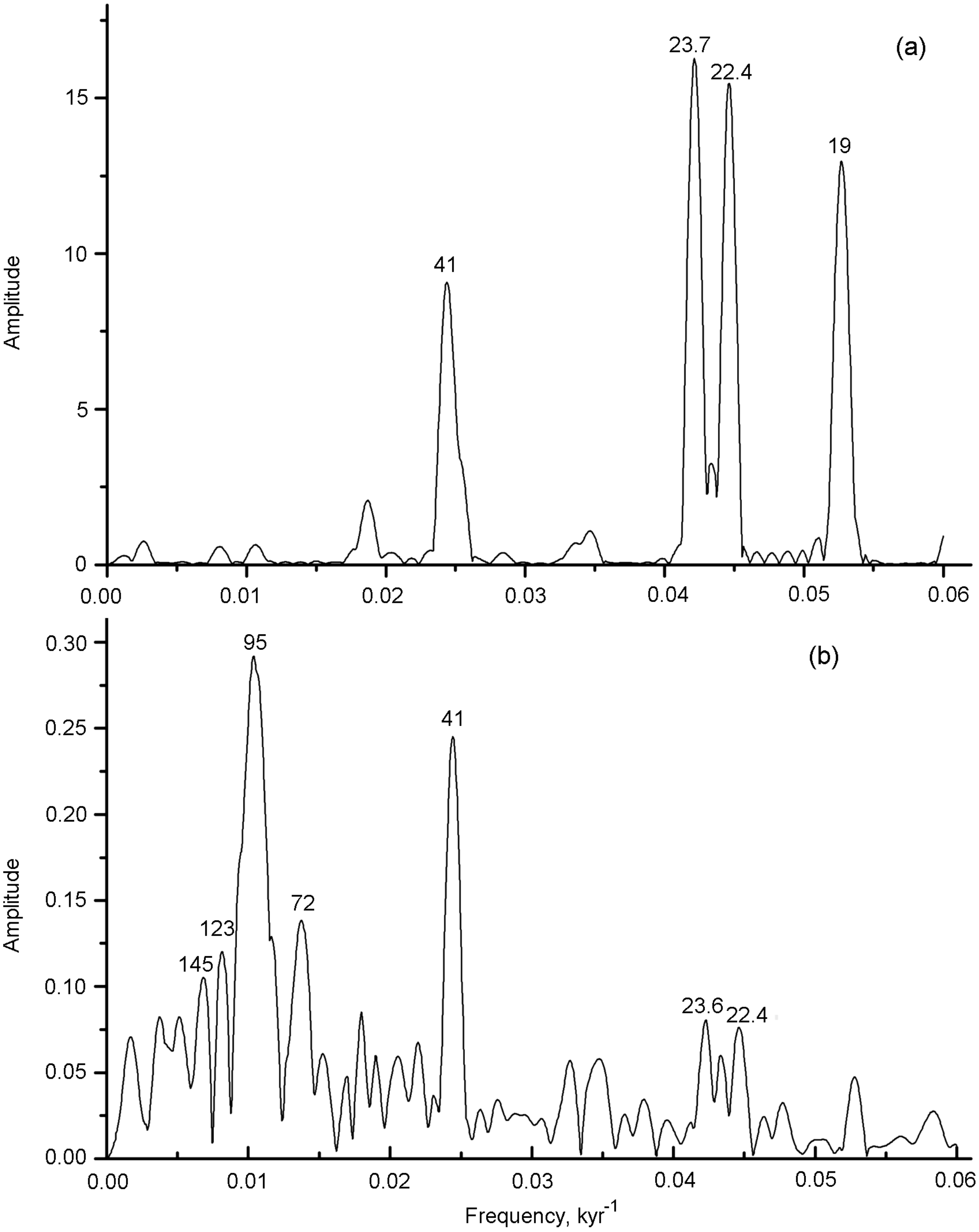

Figure 2. Periodograms: a) of July insolation at 65°N showed on Figure 1a; b) of oxygen-isotope record showed on Figure 1b. Numerical values next to peaks of each periodogram refer to the most important corresponding periods, in thousand years.

of paleoclimate orbital theory different versions long before Milankovitch. Nevertheless, it is just this incorrect Milankovitch theory interpretation that is generally accepted.

[26] In my opinion the right interpretation of Milankovitch theory could be the following. "Milankovitch theory is one of the versions of a more general orbital paleoclimate theory; the essence of the latter concerns the relationship between the global climatic variations and those of insolation caused by changes in the Earth's orbital parameters. According to Milankovitch theory, climate changes in northern hemisphere are similar to insolation variations of summer thermal half year at 65°N he calculated. In particular, the deepest minima correspond to glaciations". In support of the wording given it is noteworthy to remind that it was

the agreement between insolation diagram glaciations and those of A. Penk and E. Bruckner's Alpine stratigraphical scale that provided the grounds for the general acceptance of Milankovitch theory during the first half of the 20th century.

[27] Unfortunately, Roe, instead of original wording of Milankovitch theory, suggests a new wording, i.e., strictly speaking, a different theory [*Roe,* 2006]: "In this paper, a specific formulation of the Milankovitch hypothesis is suggested and defended: orbitally-induced variations in summertime insolation in the northern high latitudes are in antiphase with the time rate of change of ice sheet volume". Hence it may be concluded that this publication [*Roe,* 2006] is another admission of Milankovitch theory drawbacks. It is worth noting that the new wording doesn't solve any of Milankovitch theory above mentioned problems, but only makes the correlation between theory and empirical data more difficult.

[28] However, I believe that the more correct line of attack on the Milankovitch theory problems is the critical analysis of its main statements and the revealing of its main advantages and drawbacks in the course the further investigation. Such analysis was made in the following publications [*Bol'shakov,* 2001, 2003a, 2003c]. As a result, apart from its certain value due to mathematically accurate calculations of insolation variations, the following major drawbacks of Milankovitch theory have been defined.

[29] (a) To determine the variations of individual orbital elements paleoclimatic value with strictly calculated quantitative insolation oscillations, Milankovitch hasn't accounted for the qualitative variations of the oscillations. In other words, eccentricity variations cause changes of Earth-oriented total average annual heat flow. However, variations of the obliquity and precession as mentioned above do scarcely change any annual insolation of the entire Earth, causing only energy latitudinal and seasonal redistribution respectively. These significant qualitative differences of insolation change associated with different orbital elements, were neglected in Milankovitch theory. For this reason alone the quantitative parameters Milankovitch calculated to determine insolation changes can't be regarded as the global climatic effect of corresponding orbital elements real measure.

[30] (b) The method of quantitative estimation of insolation at the upper atmospheric boundary variations paleoclimatic value can't be considered as accurate. This method is based on the calculations for individual thermal half years and geographic latitudes. After all one can not believe that for half year the insolation affects the global climate and for another half year doesn't. As well as one can not assume that the insolation of one latitude determines the global climate changes in single interrelated climate system of the Earth possessing great inertia. Another reason for this method to be rejected is that the mentioned above semi-annual precession insolation variations, as well as those associated with obliquity insolation variations of high and low latitudes change in antiphase.

[31] Therefore if we calculate insolation changes that are continuous in time, i.e. annual and in space, i.e. for all the Earth latitudes, the contribution of variations related to Earth axis inclination angle and precession would be zero. Apparently, in this situation it is beyond reason to establish a theory that associates global climatic oscillations only with insolation changes caused by obliquity and precession variations, because these changes are virtually zero. Probably that was the reason for Milankovitch to use semi-annual insolation changes at certain latitudes for paleoclimatic interpretations. Nevertheless, as discussed earlier, the account of insolation changes continuous in time and space is required for the correct derivation of the theory.

[32] (c) One more trouble is much less detailed and mathematically strict (as compared to insolation variations calculation) estimation of various Earth feedbacks, which he considered not that important when compared with Croll who did it 50 years earlier. Milankovitch was not fully aware of the feedbacks' real importance and controlling role in climate changes. Milankovitch considered the quantitative variations of semi-annual insolation he calculated to be the basic factor of paleoclimatic changes.

[33] Thus M. Milankovitch affected paleoclimate orbital theory in two different ways. On the one hand, mathematically strict calculation of orbitally-determined insolation variations should be regarded as a progress in theory development. On the other hand, he attributed a disadvantage to the theory development providing a global paleoclimatic significance to discrete (semi-annual and at one latitude) insolation variations. Moreover, considering insolation variations to be the primary and direct factor defining the presence of glacial cycles, Milankovitch brought the orbital theory development back into pre-Croll time: J. Croll has already made a conclusion that glaciations can't directly result from variations of orbital elements (and from caused by these variations insolation changes, see above).

4. The Fundamental Importance and Some Peculiar Features of the Earth Feedbacks

[34] At present the need in feedbacks for transformation of the weak insolation signals into global climate changes is almost a received fact. (Moreover, some authors assume the presence of not insolation-driven, but independent, self-oscillating global climate processes resulted from the influence of feedbacks in the course of interactions in the ocean-land-atmosphere-cryosphere system). A specific example shows the importance of the feedbacks effect.

[35] To verify the mechanism of Earth axis inclination angle variations climatic influence (ε decrease resulted in insolation decrease at high latitudes causes global cooling), Croll, and then Milankovitch, used the mechanism of positive feedback resulted from albedo change due to ice and snow cover area change mainly at high latitudes. However, ε variations insolation changes of high and low latitudes being in antiphase, the solution of the problem of *global* climatic influence of angle ε variations assessment would become quite difficult in the case of positive feedback for insolation variations at low latitudes, comparable to the discussed albedo relation at high latitudes.

[36] As exemplified above the account for feedback specific character will make it easier to resolve the problem relevant to the obliquity (and, in my opinion, with precession) zero average annual insolation variations for the entire Earth. It also can be a help in the global climatic value of variations for each of the three orbital elements estimation. The various Earth feedbacks are known to exist. They are not only positive (associated either with albedo change due to snow and ice volume and vegetation cover change or with greenhouse gases quantity change), but also negative as those related to the atmospheric circulation enhancement resulting in the lowering of latitudinal temperature gradients that increase during the time of glaciation.

[37] There is a good reason to assume that these types of feedbacks variously affect the orbital signals caused by variations of individual orbital elements. For example, the positive indirect relation caused by albedo change in mainly high latitudes of the Earth is likely to enhance strongly the insolation signal associated with variations of Earth axis inclination angle whose highest variations do also occur in high latitudes. Atmospheric circulation speed changes, caused by change of temperature gradients between pole and equator are most likely first of all to influence the same orbital signal. The feedback caused by the concentration of greenhouse gases in the atmosphere of the entire Earth oscillation is most likely to highly affect the direct (not precession modulations related) eccentricity signal changing the average annual insolation of the entire Earth. Not that clear mechanism of precession climatic influence, associated in particular with paleomonsoons [*Barron et al.,* 1985; *Clemens and Prell,* 1991; *Rossignol-Strick,* 1983] is to a greater extent of regional rather than global importance, hence we can see a specific effect of the Earth feedbacks on the precession signal.

[38] Noteworthy that the above discussed was the specificity of various feedbacks forcing on certain orbital signals. However, there is still a certain possibility that all the signals are affected by the same feedbacks. An example is a crucial feedback caused by snow and ice cover albedo change [*Budyko,* 1977], that in Pleistocene forced the signals related to variations of all the three orbital elements. The albedo relation forces mostly those insolation signals that are related to eccentricity and obliquity variations, hence the ice sheets presence in the Quaternary period is the main factor defining rhythms of the Pleistocene global climatic cycles.

[39] Thus stated in Milankovitch theory identical linear forcing of insolation signals hasn't been properly verified. Such a statement confirms that Milankovitch followers had to accept a "non-linear forcing" mechanism of eccentricity insolation signal to agree with empirical data [*Berger,* 1999; *Hays et al.,* 1976; *Imbrie et al.,* 1984; 1993]. Furthermore, the same set of empirical data suggests the absence of the linear amplification postulated by these authors for those insolation changes due to variations in the axial tilt and precession as well. So, Milankovitch insolation curves [*Milankovitch,* 1930] and especially *Berger and Loutre* [1991] for 65°N show the dominance of the precession contribution, whereas in the majority of records of indirect paleoclimatic parameters 41-kyr component caused by axial tilt dominates that of 23-kyr (see Figures 1, 2). It resulted in the conclusion that the enhancing mechanisms are neither "linear" nor "non-linear", but are "individual" for the variations of each orbital element [*Bol'shakov,* 2003c].

[40] Hence, the proper account of different feedbacks is required to launch a correct paleoclimate orbital theory. It is precisely the account of the Earth feedbacks specificity in time and space that can make it possible to resolve the problem of zero average annual insolation changes of the entire Earth associated with the axial tilt and precession. Thus the real and reliable mechanism describing the climatic effect of different orbital elements variations, primarily precession, has to be developed.

[41] The conventional interpretation of precession climatic influence [*Raymo and Nisancioglu,* 2003 p. 1]: "...a glaciation can only develop if the summer high northern latitudes are cold enough to prevent the winter snow from melting, thereby allowing a positive annual balance of snow and ice" can not be considered to be actually correct . Such an interpretation is incomplete for it considers just a half of the precession forcing, "cold summer", whereas, as was discussed above one should account for a actually functioning full annual insolation cycle, i.e. long cool summer and short mild winter or long cold winter and short hot summer. It is the full annual insolation cycle for which the specific mechanism of precession climatic forcing should be found. One can not exclude that it is quite possible that Köppen's notion (long cool summer and short mild winter favouring the glaciation) might hold true to the northern hemisphere and the opposite one by Croll will be valid for southern hemisphere [*Berger,* 1980; *Bol'shakov,* 2003a, 2003c].

[42] It is also essential to remember that the colder summer results not only from the biggest distance from Sun, but also from the decrease of Earth inclination angle ε. Angle ε decrease causes average annual insolation decrease in high latitudes of both hemispheres. Caused by precession seasonal climatic contrasts are at the same time in antiphase in different hemispheres, while average annual precession insolation equals zero at any latitude. Obliquity variations result in single-phase change of average annual insolation at high latitudes in both hemispheres that is in turn forced by albedo feedback which may be considered the main reason of a stronger, as compared to precession, climatic influence of obliquity in Pleistocene. Thus as to the climatic forcing of summer temperatures mentioned above the obliquity rather than precession is to be considered as the most important. *However, the orbital forcing of monthly or diurnal insolation automatically implies that it is precession that affects greatly the insolation changes* (Figure 1, 2). The above statement leads to incorrect notions of many scientists on the predominant precession influence on global climate change in Pleistocene time.

[43] The authors of papers [*Loutre et al.,* 2004; *Raymo and Nisancioglu,* 2003] pay great attention to the hypothesis "...that a maximum in the insolation gradient enhances the poleward atmospheric transport of moisture from low latitudes... Moreover the high latitude cooling and the enhanced atmospheric transport favour the delivery of snow over the Northern Hemisphere. This mechanism thus suggests a possible direct link between annual mean insolation and glacial inception" [*Loutre et al.,* 2004, p. 9]. However it is important to remember that increased atmospheric circulation (at low

angle ε), related to temperature gradients *increase* (and not insolation gradients) *is the first of all negative feedback* as it gives rise to temperature gradients *decrease*. Such a forcing is owing to the warm and humid air transfer from low to high latitudes and latent heat release during precipitation.

[44] Thus the feedback resulted from temperature gradient would actually try to weaken the positive albedo feedback. Of course, one should always remember that the main mechanism of the obliquity signal enhancement is the Croll's albedo feedback enhancing the effect of average annual insolation of high latitudes change. It is this mechanism that mainly increases the temperature gradients and thus atmosphere circulation. The fact that positive albedo feedback is greater than that of the negative caused by temperature gradient is confirmed by the presence of obliquity variations frequency in all the paleoclimatic records.

[45] The basis for full and simple explanation of climatic changes dynamics marked by orbital periodic patterns for the entire Phanerozoic is provided by global albedo changes. The Middle Pleistocene transition, for example, may be attributed to so-called parametric resonance mechanism. (About the possibility of resonance response on eccentricity forcing the reader is referred to *Hagelberg et al.* [1991]). According to this mechanism environmental conditions change results in system parameters and its resonance frequencies change. I understand the environmental changes as directed cooling in time interval from 2 till 1 million years ago that began as early as in the Eocene. It should have caused the volume of glaciations at high latitudes change and in turn changed their inertia. A possible mechanism of climatic oscillations cyclicity change at the turn of 1 m.y. can be shown as follows [*Bol'shakov,* 2001, 2003a].

[46] Earlier than one million years ago ice volume wasn't sufficiently high and Earth surface temperature was sufficiently low to provide the extent of ice comparable to those of the Pleistocene ice sheets. The change of glaciations mainly grouped at high latitudes volume in this situation was caused by rather short-period forcing of axial tilt according to empirically found 41-kyr periodicity of these changes. Thus it may be concluded that the corresponding time constant of glacial oscillations had the same periodicity at that time. Long-period forcing of eccentricity variations and associated with them global temperature oscillations were too weak to cause ice sheets extension. It is due to these reasons the variations of corresponding 100-kyr period are not reflected in climatic records of that time interval. (Eccentricity periods found by *Clemens and Tiedemann* [1997] in oxygen-isotope record of Pliocene-early Pleistocene might well be an artefact because the amplitude corresponding climatic variations is very small). Glaciers extended with time as global cooling increased.

[47] Probably it happened about one million years ago that Earth surface temperature and glacier mass at high latitudes reached critical values with the respect to the effect of insolation changes resulted from eccentricity variations. In this case even the "eccentricity" fall of temperature was sufficient to prevent melting of glaciers extending from higher latitudes towards lower latitudes. On the other hand with glaciations mass and area growth made greater positive feedbacks due to albedo and presence of greenhouse gases in the atmosphere that in turn forced the extension of glaciation. Obviously it led to increase of time constant of glaciers extension and breakup. In my opinion it was the joint effect of these three factors that determined new rhythm pattern of glaciations during the last million years.

[48] Thus for the last million years the development of global glaciations dynamics is mainly determined by the simultaneous forcing of eccentricity and obliquity variations enhanced by positive feedbacks effect against the background of the global cooling. (Similar mechanisms of "the Middle Pleistocene transition" with ice volume increase regarded as one of the main factors has been proposed by other researchers as well [*Berger,* 1999; *Clark et al.,* 1999; *Hagelberg et al.,* 1991; *Imbrie et al.,* 1993]. However, these mechanisms do not that clearly state the leading part of eccentricity and related to Earth axis inclination variations insolation signals).

[49] According to the above proposed simple pattern the further increase of glacier volume would result both in increase of area of their distribution and extend the glacial oscillations period. Thus the growth of recent glaciation might well witness the climatic event of a longer 400-kyr eccentricity cycle which didn't show itself during the last 2 million years [*Berger,* 1999; *Imbrie et al.,* 1993]. It is this statement that has been confirmed by the published data [*Heckel,* 1986; *Veevers and Powell,* 1987] showing the 400-kyr cyclicity that expressed in ocean level oscillations took place during the maximum phase of Permian-Carboniferous glaciation! (The Permian-Carboniferous Gondwana land glaciation is known to have greater as compared to those of Pleistocene, extents, i.e. its boundary reached 30°S [*Veevers and Powell,* 1987]). It means that the above data argue for the proposed mechanism establishing the relation between the insolation variations resulted from Earth axis inclination angle and eccentricity variations, changes in ice sheets volume and rhythm of their increase and decrease.

[50] The above emphasizes the key role of the ice sheet volume as affecting the orbital periods of climatic cycles. Hence the absence of ice would result in the appearance of different mechanisms of climatic oscillations. Thus one can guess, contrary to other scientists, that there would be no climatic cycles directly related to eccentricity and obliquity variations during thermal epochs. This assumption is generally confirmed by empirical data [*Herbert and Fisher,* 1986; *Kent et al.,* 1995; *Olsen,* 1986, and others]. Thus in Mesozoic, Eocene and Miocene 23-kyr (precessional) oscillations modulated by eccentricity variations took place. Independent evidence for other orbital cycles hasn't been reported. The author has shown that the statement about direct appearance of 100-kyr eccentricity variations in records of Cretaceous by *Herbert and Fisher* [1986] is most likely to be a mistake of interpretation [*Bol'shakov,* 2003b].

5. On the Global Climatic Forcing of the Total Annual Insolation Variations

[51] Turning back to the title of paper by *Loutre et al.*

[2004] it can be mentioned again that a possible climatic influence of annual insolation is not a problematic issue. The problem is how to more correctly determine the mechanism of full annual insolation variations climatic effect.

[52] It should be noted that more than 150 years ago Herschel and von Humboldt stated that the account of full annual insolation of the entire Earth is required when climatic influence of insolation variations is discussed. Imbrie wrote on this subject: [*Imbrie,* 1982, p. 413]: "There has also been a tendency for investigators to believe they could model the response of the system from a radiation curve representing the input at a single latitude and season [e.g., *Milankovitch,* 1941; *Kukla,* 1968; *Broeker and van Donk,* 1970]. Since no one could be sure which insolation curve, if any, was the crucial one, investigators had great freedom to choose a curve that resembled a particular set of data. Understandably the resulting ambiguity did much undermine confidence in the validity of the time domain prediction. Starting in 1976, with the advent of numerical models that integrated the effect of insolation changes over all latitudes and seasons, this situation was much improved..." However, those are just words and Imbrie himself used monthly (June) insolation at 65°N for modeling and paleoclimatic interpretations [*Imbrie and Imbrie,* 1980; *Imbrie et al.,* 1993].

[53] It is also the case when we refer to Berger, Loutre and Gallee paper. These authors wrote in 1998 [*Berger et al.,* 1998, p. 616]: "Such time-depended climate models must therefore be forced only by the astronomical variations of insolation for each latitude and day...", but on the next paper of the same article they write: "June insolation at 65°N is very often used as a guideline for the analysis of climatic changes and, in particular, for ice volume changes".

[54] Six years later we find a similar case in the paper by *Loutre et al.* [2004, p. 2]: "A more general version of the astronomical theory is now widely used, especially in climate modeling where changes in insolation at all latitudes and times of the year are taken into account. Nevertheless, it is often supposed that insolation at 65°N in June can be used for comparison with most proxy records". The paper gives not a single reference to a "more general version".

[55] The use of semi-annual or monthly (diurnal) insolation for climatic modeling and paleoclimatic interpretations follows from the view of precession as a major orbital factor in control of global climate changes. For example the *Loutre and Berger* [2000] statement that the "cold orbit" (giving rise to glaciations in the hemisphere discussed) shows high eccentricity value, low value of Earth axis inclination and the Earth in perihelion in the day of winter solstice arises from this view. However, as was mentioned above such concepts are not supported by paleoclimatic data: precession periods appear only slightly in paleoclimatic records of global changes (see Figures 1, 2). Whereas Figure 3 shows that glaciations of the last million years are associated only with eccentricity curve minima, but not maxima. In this case these are not absolute eccentricity values that are important but the tendencies of its change: the value of some maxima associated with interglacials is lower than that of minima related to glaciations. (The later argues for the resonance mechanism for the explanation of 100-kyr glaciation cycles in the Pleistocene).

[56] Thus the assumption about precession variations being the main factor in control of global changes in Pleistocene turns to be incorrect. (As one remembers this idea has been developed over more than 150 years by Adhémar, Croll, Milankovitch and his present devotees). Therefore a great attention to climatic influence of average annual insolation related to Earth axis inclination angle in publications [*Elkibbi and Rial,* 2001; *Huybers and Wunsch,* 2005; *Loutre et al.,* 2004; *Paillard,* 2001; *Raymo and Nisancioglu,* 2003], seems quite obvious. It would be better if the scientists' attention in future wouldn't be focused only on the obliquity alike precession that was earlier regarded as a major tool controlling the global climatic changes. There are all the grounds that the understanding of a need to consider caused by all the three orbital elements annual insolation changes of the entire Earth and associated feedbacks will appear earlier than in the end of the 21st century.

[57] Above the assumption made earlier in publications [*Bol'shakov,* 2003d; *Hagelberg et al.,* 1991] of direct (not related to precession modulation) climatic effect of eccentricity variations through resonance mechanism has been justified. Nevertheless, such logic assumption is objectionable. For example, *Maslin and Ridgwell* [2005] believe that eccentricity cannot directly cause 100-kyr glacial-interglacial cycles. To prove the later they specify that the periods of eccentricity spectral peaks are 95, 125 and 400 kyr, while the only one 100-kyr period appears in paleoclimatic records. In fact, however, periods of approximately 95 kyr and 125 kyr occur in many oxygen-isotope records (see Figure 2 and [*Bol'shakov,* 2003b; *Rial,* 1999]). The reason why the 100-kyr peak is often not divided in oxygen-isotope records was provided by *Rial* [1999]. He showed that in order to divide the broad 100-kyr peak into the components the long-term and well chronometrized records that are in fact just a few, are required.

[58] The lack of 400-kyr periodicity in the Pleistocene paleoclimatic record (and 11th stage problem) are well explained with the given above mechanism of parametric resonance. In this case eccentricity insolation oscillations are like the mechanism triggering the main cycle of oscillation while a form of climatic response is as well defined by the forcing of other orbital signals and the state of climatic system during the time period discussed.

[59] Thus the arguments of *Maslin and Ridgwell* [2005] against the direct forcing of eccentricity insolation on the climate can be easily removed. Nevertheless these authors conclude that the 100-kyr cycle is precession-controlled. Such conclusion was based on the fact that: "*Raymo* [1997] proposed that an episodic appearance of unusually low maximum of northern hemisphere summer insolation is a critical factor in control of the following glaciation"! Neither *Raymo* [1997] nor *Maslin and Ridgwell* [2005] give any physical justification of this assumption.

[60] It should be added that to explain the 100-kyr cycle is commonly involved the so-called mechanism of "energy transfer from precession level to that of eccentricity" due to minor eccentricity insolation change compared to that of precession or related to obliquity, calculated for one month and one latitude. Nevertheless, the mechanism of such transfer is not specified. It hasn't also been explained why the

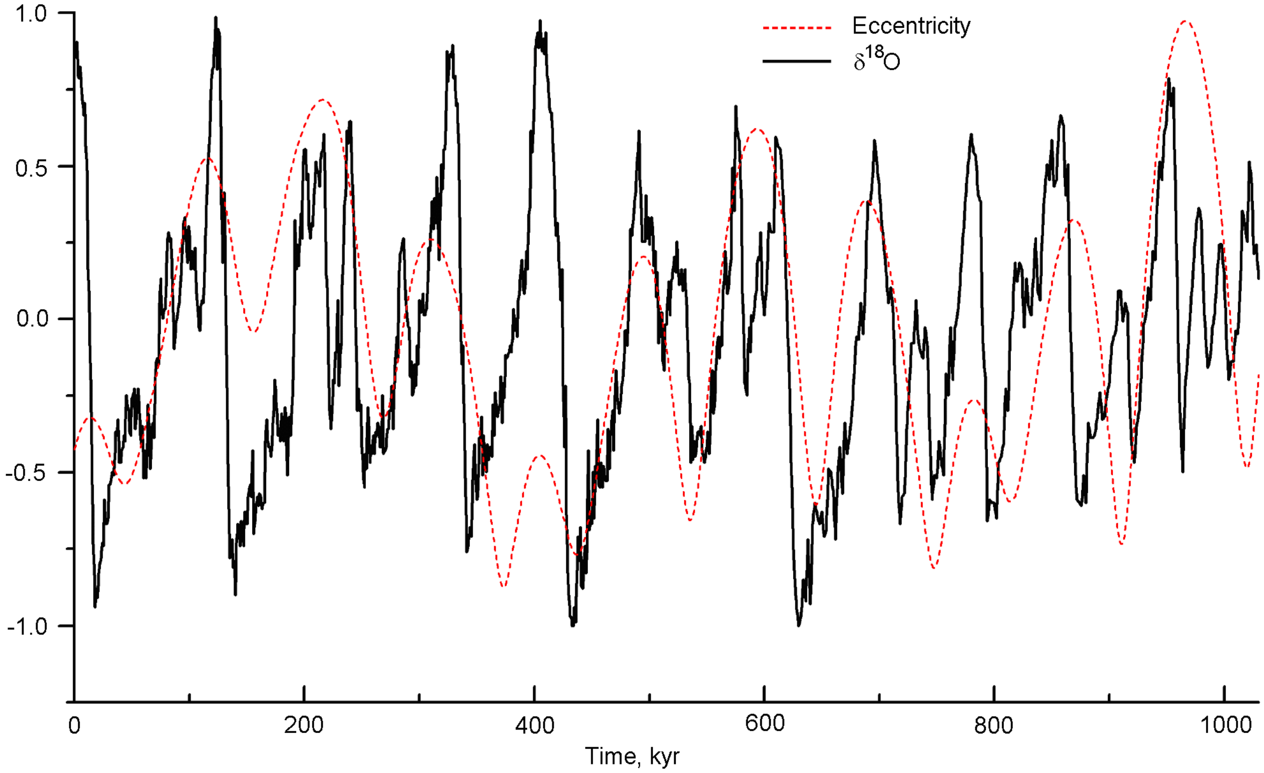

Figure 3. Correlation between the normalized eccentricity changes of Earth orbit (after [*Berger and Loutre,* 1991], dashed line) and oxygen-isotope curve LR04 (solid line). The LR04 curve is plotted in such a way that its minima correspond to glaciations. Eccentricity maxima show interglacials and minima are glaciations on oxygen-isotope curve for the last million years.

"high-energy" precession signal is the weakest in Pleistocene paleoclimatic records. Therefore clear is the tendency to complicate the explanation of the paleoclimatic influence of eccentricity variations mechanism. Unfortunately, a similar tendency appears in *Berger et al.* [2005].

[61] The authors study the origin of astronomical 100-kyr cycle. According to them eccentricity variations can't contribute that much into paleoclimatic records [*Berger et al.,* 2005]: "As the 100-kyr variations in standing insolation due to eccentricity change are too small, they cannot be the direct cause of the ice ages". Clearly, Berger et al. are true followers of Milankovitch as they focus only on *quantitative* changes in *discrete* insolation change accounting for monthly or diurnal insolation *at a single latitude.* They do not take into consideration thereby well-known (and above shown) *qualitative differences* in insolation variations related to certain orbital elements and *actually* affecting all the latitudes of the Earth all the year round.

[62] The authors consider the "variations of eccentricity, of its first derivative, of the frequency modulation of obliquity, and of the inclination of the Earth's orbit on the invariable plane of reference" to be the astronomical sources of 100-kyr signal forcing the Earth climate.

[63] The science has got a reasonable principle, never use more complicated versions to explain any phenomenon until the simple ones haven't been settled. Hence the problem stated by *Berger et al.* [2005] doesn't seem quite based. Moreover, it's again a case of baselessly complicated version.

[64] As a matter of fact it's hard to find any advantages in explanation of 100-kyr climate cycles assuming them caused not by eccentricity change, but by the change of its derivative. A definition of the mechanism of climatic influence (if it exists) due to the modulation of Earth axis inclination also should be further studied. As to the possibility of significant climatic influence of the ecliptic inclination changes, it clearly doesn't fit empirical data [*Berger,* 1999; *Bol'shakov,* 2003b]. First, the ecliptic inclination variations are characterized by a single period close to 100-kyr, whereas empirical data reveals two eccentricity periods of about 95 and 125 kyr (Figures 1, 2, 3). Second, the considerable phase difference between ecliptic inclination oscillations and corresponding climatic component has been found [*Berger,* 1999].

6. Conclusion

[65] The analysis carried out shows that the neglecting of orbital theory history resulted in significant delay of its further development. This conclusion is supported by paper by *Crucifix et al.* [2006]: "The climate response to the astronomical forcing". The summary of the paper says: "Links

between climate and Earth's orbit have been proposed for about 160 years. Two decisive advances towards an astronomical theory of palaeoclimates were Milankovitch's theory of insolation (1941) and independent findings, in 1976, of a double precession frequency peak in marine sediment data and from celestial mecanics calculations. It is recognized today that climatic interections at the global scale were involved in the processes of glacial inception and deglaciation".

[66] The extract above has some important inaccuracies. Firstly, the significant role of J. Croll in orbital theory development is not mentioned among the "decisive advances". However, the quotation given verifies the fact that Croll's discovery of feedbacks is an outstanding achievement of theoretical paleoclimatology far ahead its time. From this extract is evident that the influence of feedbacks between different components of climatic system and orbitally-caused insolation variations that Croll stated more than 130 years ago has been only "recognized today". Perhaps that is the reason why Croll's name isn't mentioned in paper [*Crucifix et al.,* 2006]? After all, if we do not consider feedbacks, it would turn out that after Croll and Milankovitch there were few outstanding achievements in theoretical paleoclimatology. In this paper [*Crucifix et al.,* 2006] Milankovitch theory is referred to not as theory of climate oscillations like Milankovitch termed it and not as paleoclimate theory like it is often spoken of, but as "insolation theory". I guess it may suggest the authors' [*Crucifix et al.,* 2006] public acceptance of drawbacks of the *paleoclimatic part* of Milankovitch theory.

[67] One can not also agree with the statement that one of the "decisive advances towards an astronomical theory" is the detection of double precession peak. Certainly, *Hays et al.,* [1976] study turned to be the strongest argument for the orbital hypothesis. However, its main result is not the detection of double precession peak (that by the way contributes the least to climatic oscillations), but the detection of 1) all the three orbital periods in paleoclimatic records and 2) phase compliance between variations of orbital elements and attributed components of paleoclimatic record. It worth mentioning that precession period in sedimentation records have been found earlier (see, for example, [*Bradley,* 1929]). However it didn't become the decisive evidence of orbital hypothesis. Furthermore, the Milankovitch theory was rejected by majority of scientists in the mid-20th century [*Imbrie and Imbrie,* 1986; *Schwarzbach,* 1950].

[68] The concluding section of paper [*Crucifix et al.,* 2006] titled "The Future of Palaeoclimate Modelling" mentions again the need for the account of global climatic interactions in development of paleoclimate astronomical models. Of course, this is a correct conclusion. I would only add that the work will be done in vain if the input signal in development of such models is again monthly or diurnal insolation at single latitude.

[69] The history development of the paleoclimate orbital theory and contemporary empirical data analysis made it possible to suggest a qualitative pattern for global climatic changes characterized by orbital periodicities for the entire Phanerozoic. Our views are based on a single system of ideas and are no contradictive. The construction of mathematically strict paleoclimatic model corresponding to these views is a very hard task. However, such a way to study the global climatic oscillations mechanisms of the past seems to be the only logic and successive. The main conclusions of our research are the following:

[70] 1. The insolational forcing expressed by the variations of monthly insolation at a single latitude shouldn't be used for paleoclimate modeling and interpretation as such input signal (i.e. June or July insolation at 65°N) doesn't *fully* account for the solar radiation change *actually* forcing the Earth's climate. Since the input signal is not valid there is not possibility to correctly define the mechanism of insolation variations transformations into the global climatic changes even if the output signal (indirect paleoclimatic records) is reliable.

[71] 2. The construction of paleoclimatic model should be accounted for continuous in time (full annual) and space (for the entire Earth) insolation variations generated by change of all the three orbital elements. The solution of the problem should also be accounted for different Earth feedbacks.

[72] 3. The main problem of orbital theory development is the elaboration of individual feedback mechanisms, enhancing the effect of every orbital element insolation signals. The forcing of feedback mechanisms on orbital signals depends on global paleoclimatic state of the Earth, i.e. can change within the geological time scales.

[73] 4. The search of individual feedbacks should be based on thorough study of diverse paleoclimatic records.

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