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How the astronomical aspects of climate science were settled? On the Milankovitch and Bacsák anniversaries, with lessons for today

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Abstract

It was 100 years ago (on August 7, 1920), that the comprehensive mathematical foundations of climate change research, written by a Serbian researcher, Milutin Milankovitch, were published. A later interpreter and developer of his results, Georg (in Hungarian: György) Bacsák (Pozsony/Pressburg/Bratislava, June 5, 1870 - Fonyód, March 4, 1970) was born 150 years ago and died at the age of one hundred, half a century ago. In this commemorative paper we look back to special circumstances in revealing the secrets of ice ages that had puzzled scientists for at least several centuries. Recently, after 100 years, the Milankovitch theory, including related short-term forcings (ranging from interannual, multidecadal to millennial timescales) has not only been confirmed, but its climate forcing mechanism has also been identified and proposed. Owing to the uniqueness of the problem, the science of the orbital forcing of climate change can be proclaimed to be essentially settled.

Keywords: Milankovitch theory; Climate change; Orbital forcing

1. An incredible story

"Mathematical theory of thermal phenomena caused by solar radiation" (Fig. 1) was written in large part in Budapest more than a century ago, in the Library of the Hungarian Academy of Sciences, under special circumstances (Fig. 2). A popular article was recently published (Szarka, 2020) and we extend our appreciation of this singular scientific achievement in this new paper. The author, the Serbian citizen Milutin Milankovitch (Milanković in Serbian and Croatian, Milankovics in Hungarian; see Fig. 3, left panel), had been dealing with this subject since 1912, but, when WWI broke out, he was arrested in his hometown Dalj (in Hungarian: Dálya), which belonged to the Austro-Hungarian Monarchy. However, through his contacts, he was able to move finally to Budapest, where the Library of the Hungarian Academy of Sciences provided him with ideal working conditions for four years throughout the war. The publication of the book (Milankovitch, 1920) was postponed until 1920 because it had to be published first in the language of the winners (Fig. 1). In the Introduction, Milankovitch reminisced the years in Budapest as follows:

> *My work thus begun was abruptly interrupted in 1914 by a new war. Prisoner of the Austro-Hungarians, I was however able to leave at the end of 1914 the prison camp and settle in Budapest, where, thanks to the hospitality*

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ACADÉMIE YOUGOSLAVE DES SCIENCES ET DES ARTS DE ZAGREB

MINISTÈRE DE L'INSTRUCTION PUBLIQUE
DU ROYAUME DES SERBES, CROATES ET SLOVÈNES

THÉORIE MATHÉMATIQUE

DES

PHÉNOMÈNES THERMIQUES

PRODUITS PAR

LA RADIATION SOLAIRE,

PAR

M. MILANKOVITCH,

PROFESSEUR ORDINAIRE DE MATHÉMATIQUES APPLIQUÉES
A LA FACULTÉ DES SCIENCES
DE L'UNIVERSITÉ DE BELGRADE.

PARIS,
GAUTHIER-VILLARS ET Cie, ÉDITEURS
DU BUREAU DES LONGITUDES, DE L'ÉCOLE POLYTECHNIQUE,
Quai des Grands-Augustins, 55.

1920

Fig. 1. The title page of the Milankovitch work published in 1920 (made largely in Budapest).

of the Hungarian Academy of Sciences, I could able to continue and complete the work in the next three work.

In his autobiographical memoir written in Serbian language (Milanković, 1952), he recalled the years of Budapest from 1914 to 1918 with fond and pleasant memories:

"Already in the first days of my stay in Pest I went to the Hungarian Academy of Sciences.
This sanctuary of science is located on the Pest side of the Danube, next to the old Chain Bridge. The building itself testifies to the service of its lofty goal: with its imposing appearance, harmonious proportions and sculptures. [...]

Fig. 2. Memorial plaque to Milutin Milankovitch (1879–1958) in the reading room of the Library and Information Centre of the Hungarian Academy of Sciences.

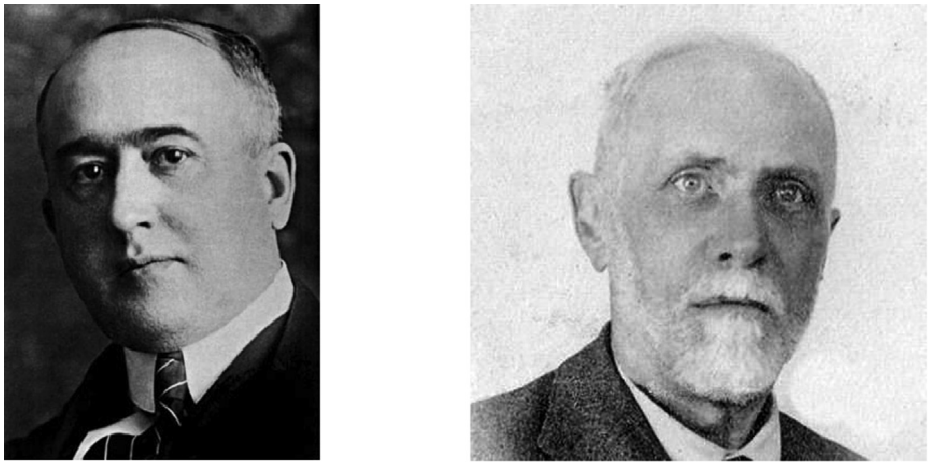

Fig. 3. Portrait of Milutin Milankovitch (1879–1958) in 1924 (left), and portrait of Georg von Bacsák (1870–1970), circa 1950 (right).

As a pilgrim who seeks to strengthen his soul and his faith in the truth, I entered this sanctuary. They announced me to the director of the Academy Library, a former professor at the technical university who was a mathematician with hair turned white: Kálmán Szily.

≪Dear Milutin≫, he said, ≪you are a professor at the University of Belgrade, a colleague of Bogdan Gavrilović, who was my disciple and whom I loved as my own son. In their journal I also published a mathematical dissertation, translated by Bogdan. ≫

During our lengthy friendly conversation, I told him what I wanted.

≪Our library's reading room≫, he said, ≪is only open to the reading public until noon, but to you for as long as you wish.≫

He then called two of the library staff and told them about me. We talked for a while longer, and then after we said goodbye, I took to the streets and sighed: I finally found a place for my research work.

I visited the Academy daily, mostly until noon. Both librarians greeted me amicably and ushered me into the spacious reading room, which was empty but well heated. I sat down in a place with a view of Buda and the rippling Danube from the window. Whenever I looked up from my work, this sight was always refreshing. My work was coming well in such an atmosphere. I brought with me the most important literature related to the issue that concerned me. All other literature was to be found in the Library of the Academy or in the Central Meteorological Institute [Royal Hungarian Central Institute of Meteorology and Earth Magnetism]. This institute was in another building on a hill in Buda. On the recommendation of Kálmán Szily, I arrived at the Institute, where the head, Zsigmond Róna, welcomed me. Thanks to this, I compiled a 144-item bibliography for my work.

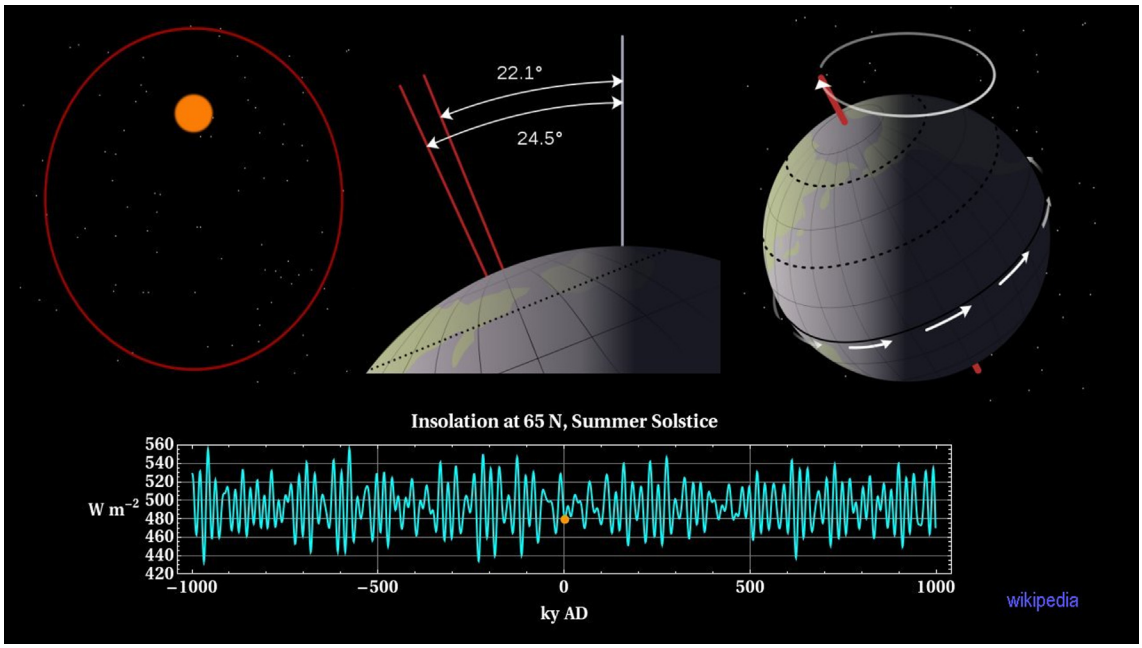

Fig. 4. Top: Illustration of the eccentricity, the obliquity and the climatic precession. Bottom: Insolation at the geographical latitude of 65°N, at the Summer Solstice of the past one million years and the next one million years. Source: https://149366104.v2.pressablecdn.com/wp-content/uploads/2015/03/milankovitch1.jpg.

In addition to the enjoyable work and the pleasant atmosphere, the days passed quickly, and to give Tinka [Mrs. Milankovitch] some joy and fun, we went to the Pest Opera. The peculiar Hungarian language, which made it impossible for us to visit theatres, was not a hindrance here. The Hungarians are very musical people, and their top state leaders have always been very generous when it comes to music. The Pest Opera has a beautiful building, a good orchestra and excellent singers. [...]

The first period of our stay in Pest seemed to us - after all we had gone through - like a belated honeymoon, and we could be sure that it was indeed when we noticed Tinka's morning sickness and all the signs that come with the blessed state. Without a family, we felt lonely abroad, so to alleviate that, we invited Danka. I wrote an application for her to be allowed to enter Hungary and handed it to the police station, where they were friendly with me. It was suggested that the application be accepted, so I soon had the permit in my hands."

Since 2017, a memorial plaque commemorates the incredible but true story in the reading room of the Library and Information Centre of the Hungarian Academy of Sciences (Fig. 2). Some of the works accurately, in line with Milankovitch, reflect the atmosphere and significance of the years:

"The Hungarian Academy of Sciences's library in Budapest was the scene of one of the most important, albeit unlikely, episodes in our understanding of the ice ages. It was here that Milutin Milankovitch was interned during the First World War. [...]

His jailers later received a telegram ordering them to remove Milankovitch to Budapest. There he was paroled on the condition that he would report once a week to the police station. A Professor Czuber, having learned that the mathematician had been imprisoned, had petitioned for his release.

When settled in Budapest, Milankovitch walked over to the Hungarian Academy of Sciences where he was welcomed with open arms by the library's director, the mathematician Koloman von Szily. Milankovitch spent the next four years in the library's reading room, making a mathematical model for the climate of a planet whose axial tilt varies and whose elliptical orbit changes, stopping by the police station periodically to demonstrate that he hadn't escaped." (Calvin, 1991)

Cvijanovic et al. (2020) independently published a note celebrating the 100th year anniversary of the publication of Milankovitch (1920) as we are writing here.

2. Clarifications and contributions

The book on the mathematical background of climate change, with periodicities of 100 kyr, 41 kyr and 23 kyr, based on corresponding variations of the orbital elements (eccentricity, obliquity and climatic precession; see Fig. 4) excited the intellectual awakening of Wladimir Köppen (the discoverer of large/significant climatic changes in the Quaternary) and his son-in-law, Alfred Wegener (the discoverer of continental drift). Lively cooperation began between the three of them. Around 1933, György Bacsák (Fig. 3, right panel) read one of Milankovitch' works in

German. He became, besides Vojislav Mišković (Janc et al., 2019), another major contributor to the development of the Milankovitch theory. A correspondence began between Bacsák and Milankovitch. In his papers, published in 1940 (Bacsák, 1940a, 1940b, 1940c, 1940d), he explained the results by Milankovitch as follows (Bacsák, 1940a): *"Milankovitch was able to go far beyond his predecessors because he divided the difficult issue of climate fluctuations in two with a clever catch, and individually coped with the halved difficulty. Milankovitch first made the calculation of the fluctuations of heat from the Sun that occur on the uppermost surface of the atmosphere, or in other words, he examined the fictitious climate that would have prevailed on Earth during the diluvium without atmosphere. Returning from a fictitious climate to reality is not an easy thing, but in Part II he also solved this difficult task precisely and arrived at the reassuring result that we can boldly use the laws of the fictitious climate, because there will only be a change in the amplitudes. In reality, here at the bottom of the atmosphere, in the biosphere, the climate oscillations are reduced by about half, but the time dates do not change and the duration of each oscillation remains the same."*

Milankovitch (1941) highlighted Bacsák's contribution in three places: on pages 371 and 512 of the English version of his tome, he thanked Bacsák for correcting spelling and calculation errors, on pages 557–558 he summarized Bacsák's merits in the following words: *"Georg von Bacsák also made a vigorous stand against the misinterpretation of my theory. He studied intensively and with success my radiation curves and he succeeded in making my theory understandable even to those who were not mathematicians. He paid more attention to the interglacial periods than I had done, by using the two component parts of the Ice Age resulting from the variations in the radiation curve, he made a distinction between the Glacial and Antiglacial, subtropical and subarctic time periods, according to the cool summers and warm summers, or mild winters and cold winters respectively, by which they were characterized. This classification enabled him to obtain a deeper insight into the climate of the Interglacial Periods of the Quaternary."*

Until 1944, Bacsák wrote a number of other studies on Milankovitch's theory, and on his related results about the interglacials (Bacsák, 1942a, 1942b, 1944). György Bacsák submitted his PhD thesis only in 1954, at the age of eighty-four, with the title *"The Pliocene and the Pleistocene in the Enlightenment of Celestial Mechanics"*. He was directly conferred the title Doctor of the Academy. The thesis was published in Hungarian and in German (Bacsák, 1955a, 1955b). Later he wrote two more papers (Bacsák, 1961, 1963). Unfortunately, neither of them has been translated into English. It is almost completely forgotten that already in 1955, an excellent real-world justification of the Milankovitch-Bacsák theory, with a detailed geological survey, was carried out in Hungary (Kriván, 1955).

Milankovitch is often said to be the discoverer of the astronomical cause of climate change. This is not the case, as this external climate-shaping force had already been considered by many scientists before him: Adhémar, Délambre, Franceur, Humboldt, d'Alembert, Croll, Herschel, le Verrier, Meech, Darwin, Legendre, A Geikie, J Geikie, Laplace, Poisson, Howorth, Wiener, de Geer, Stockwell, Gaar, Culverwell, King, Lyell, Hargreaves, Ekholm, Spitaler, Hopfner, Pilgrim (Berger, 2012). However, it was Milankovitch who wrote the first comprehensive work on the topic in sufficient mathematical detail (certainly also thanks to the ideal working conditions in Budapest between 1914 and 1918). This was his first true original contribution. Secondly, he noticed that one should focus on the changes in the winter and summer irradiations of the latitudinal belts of the northern and southern hemispheres. A clear explanation comes from Bacsák (1940a): *"Astronomically, the solar irradiance of the whole Earth all year round is always the same. In irradiance, there are only secular changes in each geographic belt and in the sum-*

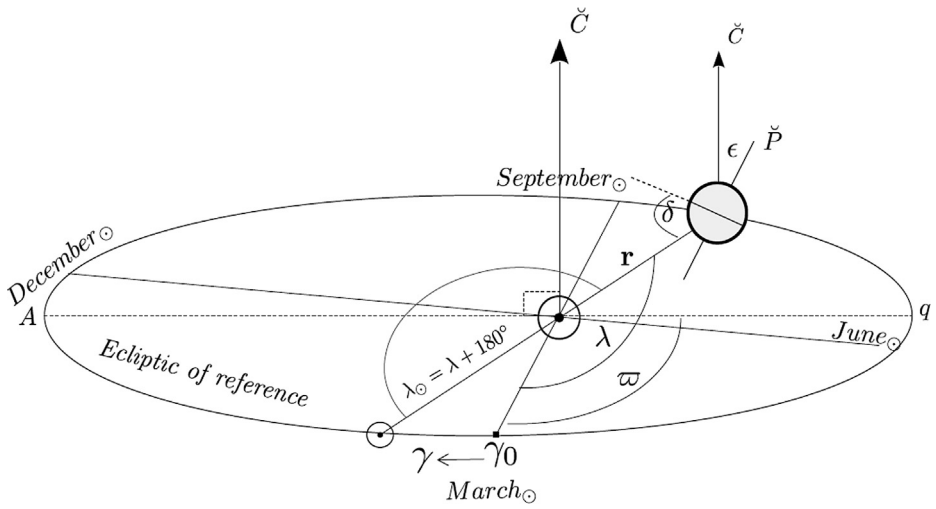

Fig. 5. The present orbit of the Earth, and the Sun in the focal point. Source: Fig. 2 of Cionco and Soon (2017).

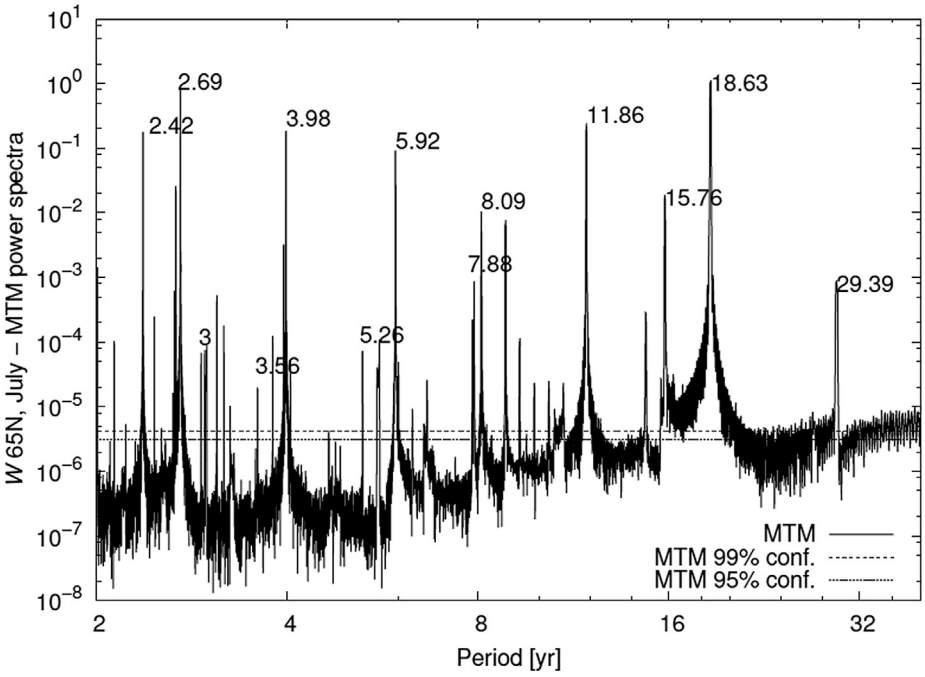

Fig. 6. The 2–40 yr spectra of the July mid-month irradiance at the geographical latitude 65°N, obtained by the MTM (multitaper) method, illustrating significant short-term orbital perturbations. Source: Figure 15 of Cionco and Soon (2017).

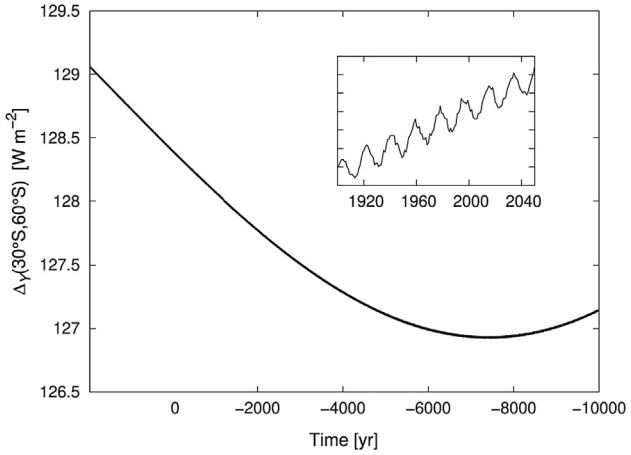

Fig. 7. The irradiation difference between 30°S and 60°S from −10000 yr to + 4000 yr. The vertical axis of the 150 year long section in the small diagram extends from 129.04 W/m^2 to 129.11 W/m^2. Source: Fig. 6 of Cionco et al. (2020).

mer and winter semesters, one belt wins or loses over the other and one semester wins or loses over the other. If these two types of gains or losses come together over time, climate fluctuations will occur. ”

Milankovitch had a third important scientific contribution, which is rarely mentioned. As it was quoted from Bacsák (1940a), Milankovitch derived many relevant equations related to the physics of the atmosphere, summarizing and completing contemporary knowledge. Among others, he specifically addressed the heat-absorbing effects of water vapour and carbon dioxide (more popularly known as “the greenhouse effect”), and had different views from that of Arrhenius and de Marchi.

3. Relevance and significance of the orbital climate theory today

The legitimacy of Milankovitch’s theory only began to be recognized in the second half of the 1970s, thanks to undisturbed deep-sea sediment series and their dating that actually depends on accurate orbital parameters (Hays et al., 1976, NAS, 1982). Had György Bacsák’s or Pál Kriván’s studies received more publicity, we contend that some of the misunderstandings might have been arguably preventable.

As it was expressed by Bolshakov (2017), misinterpretations are still common. Among others, by using the Milankovitch theory, many try to justify the *slowness* of natural climate change. But this is a dangerous and non-scientific excuse rather than any realistic examination and rejection of the relevance of orbital-seasonal theory of climate change. Thanks to the development of computer technology and the intellectual heirs of Milankovitch and Bacsák (Fedorov, 2015; Cionco and Soon, 2017; Cionco et al., 2020), it has been established that there are indeed short-term (decadal, even inter-annual) orbital forcings (STOF) in the elements of the Earth’s orbit (see Fig. 5). Fig. 6 shows the 2–40 yr spectra of the July mid-month irradiance at the geographical latitude 65°N, obtained by the MTM (multitaper) method, illustrating significant short-term orbital modulation (i.e., STOF) to the insolation forcing (Cionco and Soon, 2017). Computing the results shown

in Fig. 6 (Cionco and Soon, 2017), among others, the nutation (a lunisolar ripple deposited on the precession), the 235-month long Metonic cycle, the Jupiter and other members of the Solar System had to be taken into account. Rich temporal changes have been observed in the Latitudinal Insolation Gradient (LIG) corresponding to Bacsák's line of reasoning. Fig. 7 shows, for illustration, the irradiation difference between 30°S and 60°S from −10000 yr to + 4000 yr after Cionco et al. (2020). The LIG is presented as a perpetual climate change driver that accounts for the exact nature of the spatial–temporal variability of the orbital forcing.

In summary, we find that the orbital theory of climate change and variation, as originally proposed by Milankovitch and envisioned by Bacsák, to be mathematically robust and physically sound that its science really can be regarded as settled. Further debates should be focussed on other, as of yet little known forcings and factors and the complex filter of active processes and passive responses within the Earth climate system with different inertias. The current global and regional climate change results evidently from a superposition of human influence and a number of natural causes. We focussed here on a short-term climate forcing mechanism of astronomical origin, which does not appear to fit at all into the current IPCC's framework. This apparent contradiction may be explained because IPCC has chosen to interpret climatic change as solely originated from anthropogenic causes. In one of the latest reviews by Ramaswamy et al (2019), we read that *"a grand challenge in Earth system science lies in continuing to sustain the relatively simple essence of the radiative forcing concept in a form similar to that originally devised*". A related implication from our current historical note is that climate forcings and factors cannot be correctly categorized under the IPCC's assumptions. Climate science should be about open-minded understanding various processes and their time scales, first and foremost to understand the origin of all causes of climate change without fears nor prejudices.

Another very important but related question is, for example, whether the position of the members of the Solar System affects the solar activity itself (Cionco and Pavlov, 2018; Stefani et al., 2019) and Sun-Earth interactions (Cionco and Soon, 2017; Cionco et al., 2020). In addition to gravity, electromagnetic phenomena and couplings and connected fluid dynamics seem the key factors to be reckoned with. Many times it can be ascertained that the imagination of nature is far richer than that of man. The mysteries of the future - researchers of the terrestrial effects of an ever-changing Sun and Sun-Earth orbits - work quietly but diligently just like Milankovitch and Bacsák before them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bacsák, G., 1940a. Zur Erklärung der Interglazialzeiten. Part I Az Időjárás 16 (1-2), 43–50.
Bacsák, G., 1940b. Zur Erklärung der Interglazialzeiten. Part II Az Időjárás 16 (3-4), 98–101.
Bacsák, G., 1940c. Zur Erklärung der Interglazialzeiten. Part III. Az Időjárás 16 (5-6), 143–145.
Bacsák, G., 1940d. Die Chronologie des letzten Abschnittes des Diluviums. Barlangvilág 10 (3–4), 51–57 http://epa.oszk.hu/02800/02844/00022/pdf/epa02844_barlangvilag_1940_3-4_31-43_51-57.pdf.
Bacsák, G.y., 1942a. On the objections raised against Milankovitch's theory. Csillagászati Lapok 5 (3), 117–125 (in Hungarian).
Bacsák, G., 1942b. Die Wirkung der skandinavischen Vereisung auf die Periglazialzone. Budapest, 86.
Bacsák, Gy., 1944. The Earth History of the last 600 000 years. In: Report on the Discussion Activities of the Hungarian Royal Geological Institute. Appendix of the Report of the Hungarian Royal Geological Institute on the year 1943, Volume 6, Number 5, Budapest. http://epa.oszk.hu/03600/03638/00027/pdf/EPA03638_mafi_beszamolo_1944_05.pdf (in Hungarian).
Bacsák, Gy., 1955a. The Pliocene and the Pleistocene in the Enlightenment of Celestial Mechanics. Földtani Közlöny 85, 70-105. http://docplayer.hu/117972690-A-pliocen-es-a-pleisztocen-az-egi-mechanika-megvilagitasaban.html; Original manuscript (PhD dissertation from 1954): http://real-d.mtak.hu/1245/1/Bacs%C3%A1k_Plioc%C3%A9n.pdf (in Hungarian).
Bacsák, G., 1955. Pliozän- und Pleistozänzeitalter im Licht der Himmelsmechanik. Acta Geologica, Acad. Sci. Hung. 3, 4, 305–346.
Bacsák, G., 1961. Überblick über das Klima der Äquatorialzone. Acta Technica 37, 3 (Series Geodaetica et Geophysica), 375-402.
Bacsák, G., 1963. Die Ursache des bevorzugten Quadranten und ihr Zusammenhang mit den quartären Eiszeiten. Acta Technica 42, 435–461.
Berger, A., 2012. A Brief History of the Astronomical Theories of Paleoclimates. In: Berger, A., Mesinger, F., Sijacki, D. (Eds.), Climate Change. Springer, Vienna.
Bolshakov, V.A., 2017. On the ill-defined notion of the Milankovitch Theory and its influence on the development of the orbital theory of the paleoclimate. Her. Russ. Acad. Sci. 87, 356–369. https://doi.org/10.1134/S1019331617040025.
Calvin, W.H., 1991. The Ascent of Mind: Ice Age Climates and the Evolution of Intelligence. Bantam Books, New York.
Cionco, R.G., Soon, W.-W.-H., 2017. Short-Term Orbital Forcing: A Quasi-Review and a Reappraisal of Realistic Boundary Conditions for Climate Modeling. Earth-Science Reviews 166, 206–222.
Cionco, R.G., Soon, W.-W.-H., Quaranta, N.E., 2020. On the calculation of latitudinal insolation gradients throughout the Holocene. Advances in Space Research 66 (3), 720–742.
Cionco, R.G., Pavlov, D.A., 2018. Solar barycentric dynamics from a new solar-planetary ephemeris. Astronomy and Astrophysics 615, A153.
Cvijanovic, I., Lukovic, J., Begg, J.D., 2020. One hundred years of Milanković cycle. Nature Geoscience 13, 524–525.

Fedorov, V.M., 2015. Spatial and temporal variations in solar climate of the earth in the present epoch. Izv. Atmos. Ocean. Phys. 51, 779–791. https://doi.org/10.1134/S0001433815080034.

Hays, J.D., Imbrie, J., Shackleton, N.J., 1976. Variations in the Earth's Orbit: Pacemaker of the Ice Ages. Science 194, 1121–1132 https://science.sciencemag.org/content/194/4270/1121.

Janc, N., Gavrilov, M.B., Marković, S.B., Protić-Benišek, V., Benišek, V., Popović, L.Č., Tomić, N., 2019. Ice Age theory: a correspondence between Milutin Milanković and Vojislav Mišković. Open Geosciences 11, 263–272 https://www.degruyter.com/view/journals/geo/11/1/article-p263.xml.

Kriván, P., 1955. La division climatologique du Pléistocéne en Europe Centrale et le profil de loess de Paks. Annals of the Hungarian Geological Institute 43 (3), 441–510.

Milankovitch, M., 1920. Théorie mathématique des phénomènes thermiques produits par la radiation solaire. Gauthiers-Villars, Paris. In German: Mathematische Theorie der durch Sonnenstrahlung Wärmephänomene, Bulletin des travaux de l'Académie des Sciences de Zagreb.

Milankovitch, M., 1941. Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem. Académie royale serbe. Éditions speciales; 132 [vielm. 133]: XX, 633, Belgrade. English editions: Canon of Insolation and the Ice-Age Problem. Israel Program for Scientific Translations, Jerusalem, 1969; Zavod za Udžbenike i Nastavna Sredstva, Beograd/Belgrade, 1998.

Milanković, M., 1952. Uspomene, doživljaji i saznanja iz godina 1909. do 1944 / Успомене, доживаји и сазнања из година 1909 до 1944. Naučna knjiga, Beograd (in Serbian).

NAS, 1982. Solar Variability, Weather, and Climate. Washington, DC: The National Academies Press, page 7. doi: 10.17226/19563

Ramaswamy, V., Collins, W., Haywood, J., Lean, J., Mahowald, N., Myhre, G., Naik, V., Shine, K.P., Soden, B., Stenchikov, G., Storelvmo, T., 2019. Radiative Forcing of Climate: The Historical Evolution of the Radiative Forcing Concept, the Forcing Agents and their Quantification, and Applications. Meteor. Monogr. 59.

Stefani, F., Giesecke, A., Weier, T., 2019. A model of a tidally synchronized solar dynamo. Solar Physics 294, 60. https://doi.org/10.1007/s11207-019-1447-1.

Szarka, L., 2020. Titokfejtők - Mikor keletkeznek klímakilengések?. Természettudományi Közlöny – Természet Világa 151 (8), 361–365 (in Hungarian).