MILUTIN MILANKOVIĆ

AND THE ASTRONOMICAL THEORY OF CLIMATE CHANGES

* **Zoran Knežević** * Astronomical Observatory, Belgrade * DOI: 10.1051/epn/2010301

Is human activity changing world climate to the point of no return? A global warming trend results from a superposition of human influence and natural causes, both short term and long term. Understanding the different processes and their time scales is therefore vital to make accurate predictions about the future climate.

▲ **The Milankovic Crater in the northern territory (the Arcadia Planitia). © K. Veenenbos**

The idea that Earth's climate underwent severe changes in the geological past has become widely accepted only in the first half of the 19th century, due to the work of Playfair, Schimper, Venetz, Charpantier and many others, and somewhat later in particular of L. Agassiz [1]. They claimed that the moraines present in many alpine valleys, or the erratic granite blocks standing on the geologically unfitting bedrock are due to the fact that "the big ice-sheets like those seen at present-day Greenland once covered all the territories where such stones have been found". At the same time the expression "Die Eiszeit" was introduced in an ode written by K. Schimper. Even the famous German poet Johann Wolfgang von Goethe back in 1829 states: "to have a lot of ice a cold weather is needed, thus I presume that an epoch of great cold at least over Europe passed".

Still, there were many who opposed the idea of the Ice Ages, and the debate lasted for the entire century. At the very beginning of the 20th century A. Penck and E. Brückner [4] proposed that the glaciations took place four times in the Quaternary geological period, with three interglacial intervals of unequal duration in between. Although we now know that the climate changes were much more complex than this simple scheme predicts, the fact that the Ice Ages did take place in the past has been firmly established and not seriously disputed afterwards.

Different mechanisms have been considered to explain the changes of Earth's climate, including also astronomical ones. Soon after the publication of Agassiz' work, J. Adhémar [2] proposed that the precession of the Earth's axis of rotation is responsible for the Ice Ages. Although the simple mechanism he considered was soon rejected, Adhémar actually showed that the astronomical and geological phenomena can be related, and that the long term variations of the Earth's motion can possibly lead to climate changes.

The most remarkable early theory of the Ice Ages, which consistently combined the achievements of different sciences, was undoubtedly the theory by J. Croll [3]. Croll correctly interpreted the influence of the eccentricity of Earth's orbit upon the duration of the seasons and its coupling with the precession of the rotation axis. He was the first to consider the changing obliquity of the rotation axis, thus completing the list of relevant astronomical mechanisms causing climate changes. He also pioneered the idea of the feedback effect due to the reflectance of the incoming radiation from the surface covered by ice, and proposed that the eccentricity-driven amplification of the ocean currents augments the heat exchange between equatorial and polar regions.

Croll's theory at first attracted geologists, but it has soon been found that its results do not match the observations. As later explained by Milanković, the failure of Croll's theory is due mostly to the fact that the influence of the variable obliquity of the Earth's axis of rotation upon the insolation was not properly taken into account. Although his results were not correct, Croll was the one who laid the foundations of a comprehensive multidisciplinary approach to the climate change study, which eventually led to our contemporary understanding of these complex phenomena.

Following Croll, there were several attempts at improving his theory and results (Ball, Pilgrim, Hargreaves, Spitaler), but with not much success. The most important astronomical theories of the Ice Ages were therefore critically discussed by the great Austrian climatologist J. Hann , who concludes that the effects proposed as giving rise to climate changes are not strong enough, so that from the astronomical viewpoint one could rather expect that Earth's climate is more stable than variable.

This was the situation with the astronomical theory of climate changes when Milutin Milanković (Eng. Milankovich or Milankovitch, Ger. Milankovitsch) stepped onto the scene.

Milutin Milanković (1879-1958): biographical notes

▼ FIG. 1: Milutin Milanković. Photo from 1922.

Milutin Milanković was born on May 28, 1879 in Dalj, in the Austro-Hungarian Empire (nowadays Croatia). He was the eldest of the seven children of a Serbian family of local merchants and landlords. Being of sensitive health, he received his elementary education at home (in "the classroom without walls"), learning from his father Milan and from the private teachers, but also from numerous relatives and friends of the family, some of whom were renowned philosophers, inventors and poets. The secondary school he attends in nearby Osijek, completing it in 1896. The same year he enrolls in Civil Engineering in Vienna, and graduates in 1902 with the best marks. Only two years later he becomes the first Serb with a PhD degree in technical sciences. In a short, but amazingly successful engineering career he worked for a company specialized in reinforced concrete and built dams, bridges, aqueducts and factory halls throughout the Austro-Hungarian Empire and eastern Europe. How good he was in this work is best illustrated by a decision of his professors to apply Milanković's system in the reconstruction of one of the wings of the Vienna Technical High School itself.

It was his persistent wish to become a scientist which made Milanković take over the chair of applied mathematics at the University of Belgrade in 1909. He remained professor for the next 46 years, giving the last lesson to the students in celestial mechanics in 1955. He became a member of the Serbian Royal Academy (Serbian Academy of Sciences and Arts) in 1920, serving as its vice-president from 1948 until his death. For a brief period he served as Dean of the Faculty of Philosophy and later also as the Director of the Astronomical Observatory of Belgrade.

Soon after settling down in Belgrade Milanković learned about the problem of climate changes, to which he would devote most of his time and effort in the decades to come. He published the first paper on the subject as early as in 1912, and collected all he had done in his seminal "Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem" [7], completed in 1941. He was also the first to calculate the temperatures on the inner solar system planets; he developed a theory of secular motion of Earth's poles, worked on the reformation of the Julian calendar and occasionally on the theory of relativity. He authored several textbooks, a number of popular books on the history of science, as well as a comprehensive autobiography.

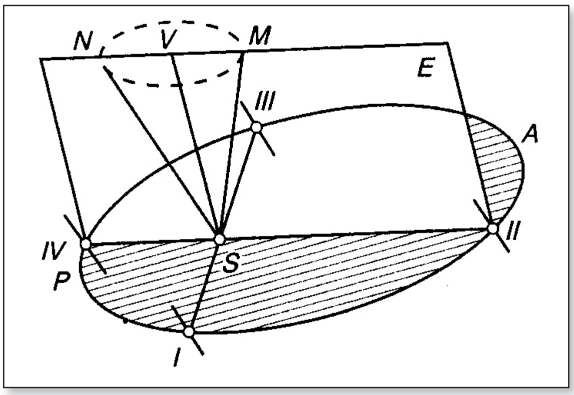
Milanković passed away on December 12, 1958, and is buried in the family vault in his native Dalj.

The Astronomical Theory of Climate Changes

The orbital forcing of climate changes is based on the astronomical mechanisms giving rise to the changes of insolation (the amount of radiation received at the top of the atmosphere of the Earth), and on the physical mechanisms governing propagation of the received energy through the atmosphere and the response at the Earth's surface. We shall describe the astronomical mechanisms here, closely following Milanković's explanations as given in the "Kanon".

The astronomical mechanisms giving rise to the changes of insolation are three: the secular variations of the eccentricity of the Earth's orbit, the precession of the Earth's axis of rotation, and the variations of the obliquity of the rotation axis. A schematic representation of the three mechanisms is given in Figure 2. Here, S is the center of the Sun, SV is perpendicular to the Earth's elliptical orbit (the ecliptic), and SN parallel to the Earth's axis of rotation, perpendicular to the equatorial plane. The angle VSN represents the inclination of the axis of rotation or the obliquity of the ecliptic.

The eccentricity of Earth's orbit changes with time, due to perturbations by other planets. The changes are quasi-periodic, have different amplitudes, and take place on different time scales. For the problem of ice ages during the Quaternary the most important changes are



◄ FIG. 2: Scheme to represent the astronomical mechanisms giving rise to climate changes (see text). From Milanković's "Kanon".

those with periods of about 100,000 years (actually this is a set of terms due to interactions of terrestrial planets with Jupiter and to their mutual interactions) and of 405,000 years (an indirect effect due to interaction of Venus with Jupiter), modulated by a number of effects of shorter and longer periods [5]. The variation of the eccentricity affects the distance of the Earth from the Sun in the perihelion P, when the Earth is closest to the Sun, and in aphelion A, when it is farthest away (see Figure 2); this changes the amount of solar radiation received at the Earth, inversely proportional to the square of the distance. The eccentricity variation also affects the duration of the seasons, thus changing the average amount of daily insolation received at the Earth in the summer half and in the winter half of the year. The cardinal points I and III in Figure 2 denote the equinoxes, the beginning of the spring and autumn, while points II, and IV denote the northern hemisphere summer and winter solstices, respectively (opposite for the southern hemisphere). Since the eccentricity of the Earth's orbit changes in a narrow range, from essentially 0 to approximately 0.06, this only marginally affects the total amount of radiation received at the Earth, but rather more significantly the duration of the seasons.

The precession of Earth's axis of rotation was known already in the ancient times, but it was only I. Newton who showed that it is due to the non-spherical shape of the Earth. Our planet has an equatorial bulge, and the gravitational attraction from the Moon and the Sun causes a retrograde rotation of the axis so that the nodes of the equatorial plane, the equinoxes, move in the direction opposite to the daily rotation of the Earth. The axis describes the circular cone NSM, depicted in Figure 2. The corresponding plane E, which contains the axis and the solstices, moves clockwise around the axis SV, completing a full revolution in about 26,000 years (the Platonic year). Due to the perturbations from the planets, the major axis of Earth's orbital ellipse, connecting perihelion and aphelion, moves counterclockwise, towards the cardinal points. Therefore these points perform a full revolution (from perihelion to perihelion) in about 21,000 years. The position of the axis is given by the value of the longitude of perihelion with respect to the moving point of vernal equinox (in other words, the longitude of perihelion with respect to the moving vernal point is given by the sum of the longitude with respect to the fixed vernal point and the precession).

It is this motion of the axis that, coupled with the eccentricity, determines the length of the seasons and affects the climate. When, for a given eccentricity, the longitude of perihelion attains 90°, the lengths of the summer half-year on the northern hemisphere is very near its maximum, and that of the winter half-year near its minimum. The total amount of radiation received in the summer half of the year is being distributed over a longer time span and the average radiation per unit time drops to its minimum. The opposite happens in the winter half-year, with an increase in average radiation. This reduces the seasonal contrast on the northern hemisphere, favoring the formation of permanent ice. At the same time, the opposite happens at the southern hemisphere, where the seasonal contrast gets amplified, resulting in short warm summers during which all the ice formed during long cold winters actually melts. When the longitude reaches 270°, the same happens, but with the roles of the hemispheres exchanged. Now the seasonal contrast is at a minimum on the southern hemisphere, and at a maximum on the northern hemisphere. When the longitude is 0° or 180° the annual seasons are of equal duration, and both hemispheres stand on par.

Perturbations by planets also change Earth's obliquity. Currently, the obliquity amounts to some 23.5°, which is close to its mean value over the period of about 41,000 years. The oscillations can be quite irregular from one cycle to another in terms of the maxima and minima, retaining however an amplitude within a narrow range of approximately ±1.3°. The obliquity also shows a steady, nearly linear increase over a very long time span, interrupted by a sharp drop close to the present, due to the passage through a secular resonance [5].

Although the changes in the obliquity are rather small, they give rise to significant climate variations. An increase of the tilt of Earth's axis increases the incident angle of the solar radiation at the poles, thus also increasing the amount of heat received at the surface and the resulting temperature. At the same time this causes very little change at the equator, thus reducing the geographical contrast of the insolation (note that at an obliquity of 54° the difference between polar and equatorial region would vanish entirely). On the other hand, an increase of the obliquity augments the seasonal contrast of the insolation, both contrasts being simultaneously reduced and accentuated on both hemispheres. Put together, the three astronomical mechanisms described above, with their coupled effects and complicated short and long term variations, give rise to changes in

Earth's insolation and thus in its climate. The three basic cycles of these changes of 21,000, 41,000, and 100,000 years are often called "Milanković's cycles".

A full account of the physical part of the theory of climate changes is outside the scope of this short review, thus we shall conclude with the final result of Milanković's work, his famous curve representing the secular variations of the summer insolation, shown in Figure 3.

Concluding remarks

Although Milanković did not discover the astronomical mechanisms described above, nor was the first to recognize their importance for the climate changes, he certainly was the first to fully comprehend and mathematically rigorously determine their place in the complicated interplay of various factors. Let us quote in this regard J. Laskar and his collaborators [5]: *"Since then, the understanding of the climate response to the orbital forcing has evolved, but all the necessary ingredients for the insolation computations were present in Milankovitch's work."*

Milanković was perhaps not the first to consider the insolation distribution or to suggest a particular choice of the indicative latitude or time of the year in which to compare the results, but he was the first to accurately compute the climate response to the insolation forcing. Nor may he have been the first to compute each individual step of the astronomical theory of climate changes, but he was the first to compute, in full detail and with necessary precision, all three steps: the astronomical parameters, the insolation and finally the climate response. It is therefore that he can be called the father of climate modeling.

Milanković's theory was the first of its kind that could be confronted with the evidence from other sciences and verified through independent research. He did, however, not live to see the theory proven. Although many data have already been collected in the 1950's, the real breakthrough came only after his death, in the mid 1970's, with the results of the CLIMAP project [6]. Since then a great number of data has been gathered confirming the role the orbital forcing in shaping of the climate of the Earth. This also brought a well deserved recognition to the pioneers of this scientific achievement and to Milutin Milanković in particular: craters on the Moon and Mars bear his name, as well as an asteroid (1605 Milankovitch). In addition, the European Geosciences Union established a Milutin Milanković Medal for outstanding achievements in long term changes and climate modeling. A big boulevard in Belgrade as well as several schools and astronomical societies throughout Serbia bear his name to preserve the memory of the great scientist with his people. ■

About the author

Zoran Knežević is a Serbian astronomer. His major scientific contributions are in the field of movement of small celestial bodies. As of 2002, he is the director of Astronomic Observatory of Belgrade and the president of Serbian National Astronomy Committee.

References

[1] L. Agassiz (1840), *Études sur les glaciers,* Neuchatel.

[2] J.A. Adhémar (1842), *Révolutions de la mer, déluges periodiques,* Paris: Bachelier.

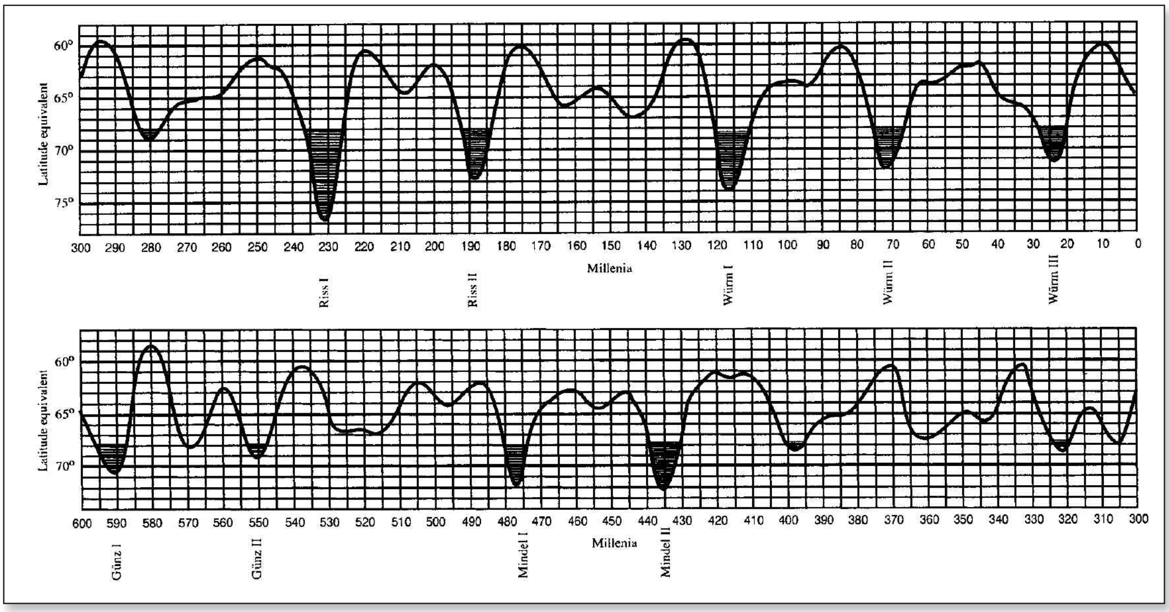
[3] J. Croll (1889). *Discussions on Climate and Cosmology.* London.

[4] A. Penck, E. Brückner (1901-1909). *Die Alpen Im Eiszeitalter.* (3 Vols.) Leipzig: Tauchnitz.

[5] J. Laskar, P. Robutel, F. Joutel, M. Gastineau, A.C.M. Correia and B. Levrard (2004), *Astronomy and Astrophysics* **428**, 261.

[6] J.D. Hays, J. Imbrie and N.J. Shackleton (1976), *Science* **194**, 1121.

[7] M. Milankovitch (1941), *R. Serb. Acad., Spec. Publ.*



► **FIG. 3:** The secular variations in summer insolation for 65° North over the past 600,000 years, given in terms of latitudinal variations. For example, some 10,000 years ago the insolation at 65° was the same as that at 60° nowadays, and the insolation around 230,000 years ago was the same as the present one at 77°.