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Astronomical solutions for paleoclimate studies. Historical views and new challenges.

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According to Milankovitch theory (1941), the large climatic changes of the past originate in the variations of the Earth's orbit and of its spin axis resulting from the gravitational pull of the other planets. These variations can be traced over several millions of years (Ma) in the geological sedimentary records, although the mechanisms that transfer the forcing insolation to the climate response and variations of the sedimentary record are not precisely known.

The first paleoclimate models of Croll (1890) and the pioneered work of Milankovitch (1941) were based on the analytical theory of Le Verrier (1846, 1856). Since then, most of the work done in paleoclimate studies have been correlated with planetary solutions elaborated at Paris Observatory. Le Verrier solutions were improved by Bretagnon (1974), and since 1990, most of the works in paleoclimate use the long term semi-analytical solutions of (Laskar et al, 1988, 1993), and the numerical ones from (Laskar et al, 2004).

A decisive improvement has been achieved with the elaboration of the INPOP ephemerides (Fienga et al, 2008, 2009, 2011, 2014, 2015, 2018), and the released of the long term solution based on INPOP (laskar et al, 2011). This allowed to extend the orbital solution up to 50Ma. At the same time, we could demonstrate that due to the perturbations of Ceres and Vesta, it will never be possible to elaborate an orbital solution valid over more than 60 Ma (Laskar et al, 2011b).

For the rotational motion of the Earth, the situation is very different. The spin of the Earth is affected by the tidal torque of the Moon. This can be computed, and we do it with great accuracy in INPOP, using the Lunar Laser Ranging data, but this will be valid only over a few hundreds of years over the present date. The largest uncertainty in the solution is then the unknown of the evolution of the tidal dissipation over time, and we cannot be assured of the accuracy of the precession solution beyond 20 Ma.

For decades, the astronomical solutions have been used as an input for stratigraphic time scale calibration and paleoclimate studies. The next challenge is to use the correlation between the geological record and the astronomical computations to extend the astronomical solutions beyond their horizon of predictibility, both for the orbital and rotational motion of the Earth. This will require very long continuous stratigraphic records of good quality and sophisticated analysis methods. Several recent results show that this goal can be reached in the next decades.