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# Is the astronomical forcing a reliable and unique pacemaker for Climate?

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Evidence of glacial/interglacial asymmetric cycles over the last millions years of the Plio/Pleistocene have been found in Paleoclimatic records. The fact that deglaciations occur much more rapidly than glaciations indicates that the underlying dynamics is very likely to be a slow-fast dynamics, like the one of relaxation oscillators; hence this model will be used here (more precisely, a van der Pol oscillator, slightly modified in order to better reproduce these cycles).

The astronomical forcing is often said to be a 'pacemaker' of ice ages (Hays et al. 1976). The underlying idea is that ice ages are a manifestation of dynamics internal to the climate system, but their timing is set by the astronomical forcing. This interpretation may be linked to the universal concept of synchronization in nonlinear sciences and in dynamical system theory. Here, we go a step further in the study of such a synchronization by investigating its robustness and uniqueness.

First, for investigating the robustness of the synchronization, we combine local and global views of the dynamics, given by 2 indicators: the local largest Lyapunov exponent, and the evolving geometry of the basins of attraction due to the aperiodic insolation. We find that even if the attracting trajectories are Lyapunov-stable on a long term, there exist positive values of the local Lyapunov exponent, so that climatic orbits could diverge for some period of time (50 kyr typically), due to a small perturbation. Moreover, as the attracting trajectories can sometimes lie quite close to the boundary of their basins of attraction, a small perturbation could cause a kind of phase slip, reducing predictability. The Climate could then potentially jump from one to another climatic trajectory.

By the help of bifurcation diagrams, we also show how and under which conditions (e.g. on the insolation forcing strength) such a synchronization can occur. We compare the results for 2 different types of insolation forcing: the real complex (aperiodic) insolation forcing, and a smooth periodic forcing, which is better understood and more easily interpretable. We underline the specificity of the insolation forcing.

Then, we discovered that multiple possible locking states (attractors) could coexist for a the system, and that the number of these is controlled by some parameters (like the amplitude of the insolation forcing). This is a particularly interesting result, as there is an apparent contradiction with the uniqueness hypothesis of [Tziperman et al, "Consequences of pacing the Pleistocene 100 kyr ice ages by nonlinear phase locking to Milankovitch forcing. Paleoceanography", 21:PA4206, 2006].

In order to automatically count the number of attractors, we used an appropriate clustering technique. We then show on the same kind of bifurcation diagrams, that within the regions of synchronization previously identified, the number of attractors can vary, and how. We again compare the results for the same 2 different types of insolation forcing as above. The peculiar feature of intermingled Arnold's tongues for the case of the aperiodic insolation forcing brings lots of physically insight into the way the number of attractors is defined; it may indeed be related to the major components of the insolation forcing in a striking way.