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Modeling past abrupt climate changes: driven oscillators and synchronization phenomena in Paleoclimate theory

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According to Milankovitch theory of ice ages, summer insolation at high northern latitudes drives the glacial cycles, i.e. the growth and reduction of Northern Hemisphere ice sheets, and there is evidence that astronomical forcing controls indeed the timing of Pleistocene glacial-interglacial cycles. However, the $\delta^{18}O$time series (the $\delta^{18}O$ is a proxy for global ice volume) available for the last few million years reveal a non-linear response of the climate to the external forcing: transitions from the glacial to the interglacial states occur more rapidly than the transitions from the interglacials to the glacials, resulting in the so-called *saw-tooth* shape of the signal. These terminations were very abrupt compared to the smooth changes in insolation. Moreover, insolation alone cannot explain the Mid-Pleistocene transition. During this event, occurred about one million years ago, the dominant *41 kyr* glacial cycles, were replaced by longer *saw-tooth* shaped cycles with a time scale around *100 kyr*. The asymmetry in the oscillations indicates a non-linear response to the orbital forcing, expressed through a bifurcation, or tipping point. As an introduction to the problem, we studied simple driven oscillators that can exhibit asymmetric oscillations between the glacial and interglacial states under the effect of the astronomical forcing, such as the Van der Pool and the Duffing oscillators. In order to understand how these simple low-dimensional models enter theories of ice ages and rapid events, we studied synchronization phenomena between simple driven oscillators and astronomical forcing, focusing on distinguishing between the so-called *resonance scenario* and the so-called *phase locking* scenario. We next examined the possible mechanisms for the Mid-Pleistocene transition. Here we show that the transition could be explained as a result of frequency-locking to the external forcing. This change can be interpreted as a result of an internal change in climate response (that might correspond, for example, to the decrease of global CO_2), since it does not correspond to any changes in the orbital forcing.