Unifying Strong and Weak Pyramidal-Interneuronal-Gamma (PING) Rhythms with a fully solvable model of phase oscillators

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The interplay between excitation and inhibition is a prominent mechanism of generation of neuronal oscillations. These rhythms, usually called Pyramidal-Interneuronal-Gamma (PING) oscillations, are observed in mathematical models of large populations of interacting excitatory (E) and inhibitory (I) neurons. These models show that, in the PING mechanism, oscillatory cycles begin with an excitatory boost of activity, followed by an inhibitory increase of activity. Additionally, the PING mechanism manifests itself into two distinct dynamical regimes often called "strong" and "weak" PING. In strong PING, both E and I neurons fire regularly at the population frequency. Conversely, in weak PING, E neurons fire sparsely, with a firing rate much lower than the frequency of global oscillations. Recently, a two-population Kuramoto model (KM) has been shown to account for the main features of strong PING rhythms (Phys. Rev. Lett. 120, 244101, 2018). However, a description of weak PING using reduced, analytically tractable phase oscillator models is lacking, as well as a unified explanation of both weak and strong PING rhythms. Here we show that an extension of the E-I Kuramoto model, which considers intrinsic properties of E and I neurons (i.e., their phase resetting curves), fully accounts for both weak and strong PING regimes. Indeed, besides the standard fully synchronous states analogous to strong PING oscillations, the model displays a novel class of quasiperiodic partially synchronized states where E cells fire at a lower frequency than I cells. Remarkably, such partially synchronous states arise in parameter regimes that agree with weak oscillations found in numerical simulations of biophysically realistic models. Our results represent the first complete understanding of the emergence of PING rhythms in terms of simple, exactly solvable phase oscillator models.