Pulses that organize: Collective pattern formation in swarmalators

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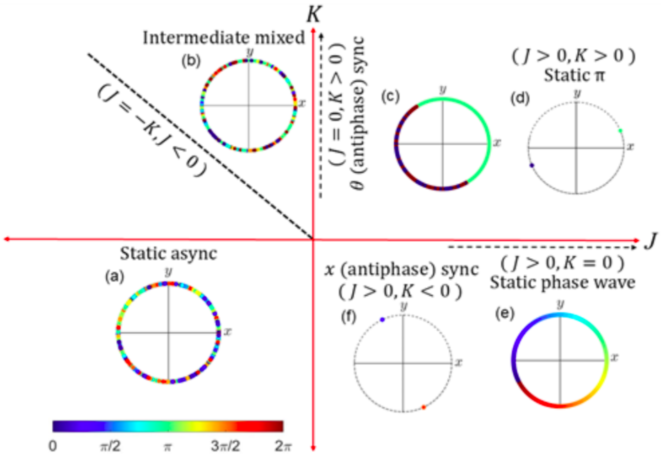
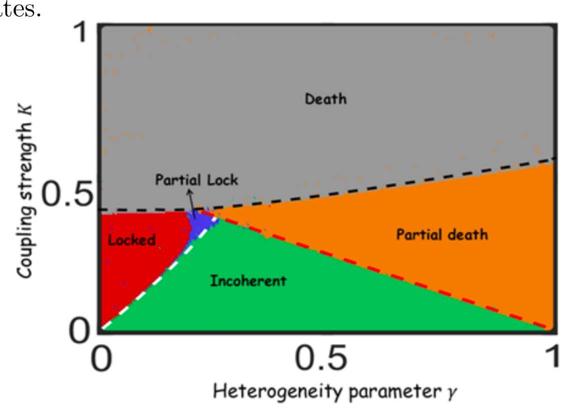
The physics of complex systems seeks to unravel the fundamental mechanisms by which collective, self-organizing behaviors emerge from the interactions among various individual components. In nature these collective patterns often involve two intertwined processes: spatial movement and rhythmic activity in time. Swarmalators describe a distinct class of system that couples spatial dynamics with internal rhythmic behavior. These are the kind of self-propelled particles whose spatial motion emerges from the collective aggregation of the swarming agents, while their internal dynamics are characterized by intrinsic oscillatory behavior. The model captures a diverse range of collective patterns that closely mirror real-world phenomena. In particular, the static phase wave is reminiscent of the aster structures observed in ferromagnetic colloids, while the active phase wave mimics the vortex arrays visible in the population of spermatozoa. Clustered states capture the collective migration in bacterial colonies or chemical cell aggregation, whereas the chimera-like states, characterized by the co-existence of both ordered and disordered groups, resemble neural activity patterns in cortical networks. To date, the Kuramoto model remains the predominant framework for describing each oscillator's intrinsic phase dynamics. Apart from this, several well-studied biological phenomena, such as flashing fireflies, Japanese tree frogs croaking, neuronal spike trains, rhythmic clapping in crowds, and technical systems such as communications in wireless sensor networks or drone swarms, involve pulsatile rather than continuous interactions. For instance, in certain species of fireflies, individuals communicate through brief, discrete flashes of light (pulses rather than continuous signals), often leading to synchrony or antiphase flashing patterns over time. In 1967, Winfree proposed a model by introducing globally coupled oscillators where agents communicate through signal emission and response [1]. The system exhibits a remarkable transition from asynchrony to synchrony, closely resembling the phase transition in statistical mechanics. Therefore, plugging the Winfree system into generic swarmalator dynamics can provide a more comprehensive and biologically relevant paradigm for modeling their collective behavior. In our work, we study a simple 1D swarmalator ring model where interactions occur through brief, discrete pulses. We have checked the system for both identical [2] and non-identical [3] swarmalators. This general interaction approach reveals rich collective patterns (including similar and novel states), and we successfully analyze the stability thresholds for the states.





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