Noise Effects and Spin Waves in Hydrodynamic Spin Lattices

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with collaboration from Dr. Pedro Sáenz and Ray Qu

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Hello! My name is Michael Edwards and this is Noise Effects and Spin Waves in Hydrodynamic Spin Lattices. I represent the Physical Mathematics Laboratory, a group that tackles prominent questions in physics and engineering, with a growing number of interdisciplinary projects. Our work includes theory, simulations, and experiments. These slides encompass my progress over the last year in collaboration with Dr. Pedro Sáenz and Ray Qu.

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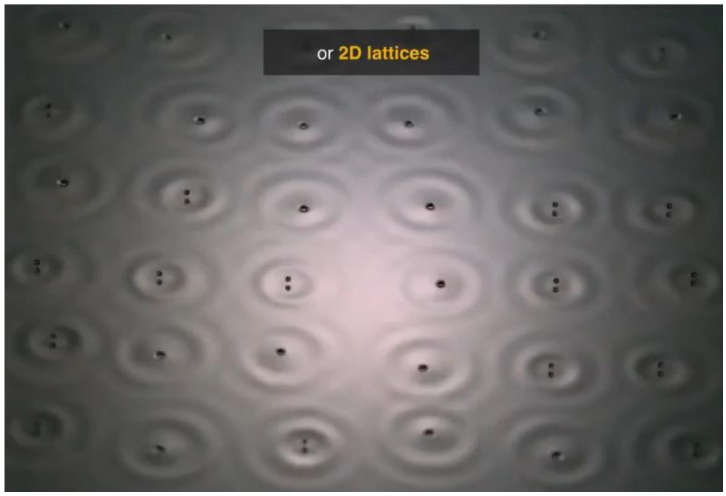
Hydrodynamic Spin Lattices



Credit: Sáenz, P.[2,3]

So what are Hydrodynamic Spin Lattices? These are arrays of bouncing droplets on a vibrating fluid bath that are self-propelled by the waves they generate. These 'walking droplets' are an analog to quantum wave and particle behaviors, and may be arranged in 1D and 2D lattices. Foremost, we observe their tendency for synchronization.

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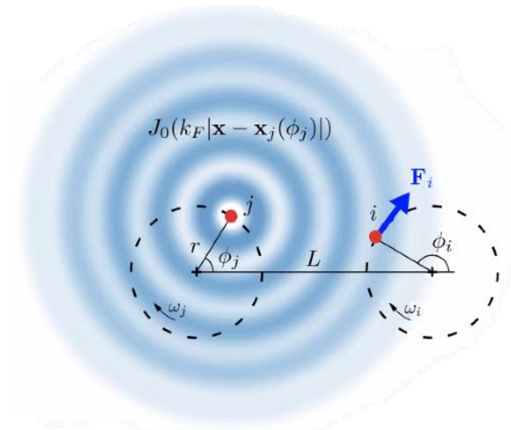
The HSL Model

$$\dot{\phi}_i = \omega_i$$

$$\dot{\omega}_i = \underbrace{\frac{1}{\tau}\left[1 - \frac{\omega_i^2}{\omega_0^2}\right]\omega_i}_{\text{Rayleigh}} + \underbrace{\sum_{(i,j)} F_{i,j}}_{\text{Coupling}}$$



$\tau = 0.1$, $\omega_0 = 1$

We simulate this behavior with a system of differential equations that captures the phase and rate of rotation of these spins, and was designed over three years before I entered the scene. The phase, phi is measured as the angle of the spin with respect to the line connecting the wells between spins, and the rate of rotation, omega, includes clockwise and counter-clockwise rotation. Omega is influenced by a Rayleigh term, which tries to reach the preferred speed, omega-naught, of 1 as quickly as allowed by tau, here 0.1. While this term applies to a single spin, our coupling term communicates between spins to achieve same-direction rotation.

Arriving at Coupling

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$$U = \alpha\left(\cos(\phi_i) - \cos(\phi_j)\right)^2 + \beta\left(\sin(\phi_i) - sin(\phi_j)\right)^2 \quad (1)$$

$$F_{i,j} = -\frac{dU}{d\phi_i} \quad (2)$$

$$= \tilde{\alpha}\sin\left(\phi_j - \phi_i\right) \qquad \tilde{\alpha} = 15 \quad (3)$$

This coupling is the negative derivative (2) of the potential of the system (1), which has an alpha and beta term for horizontal and vertical corrections. For our system, alpha and beta are equal, and as a result the term simplifies to a compact result (3). This coupling has the fairly unique ability of undulating between positive and negative corrections.

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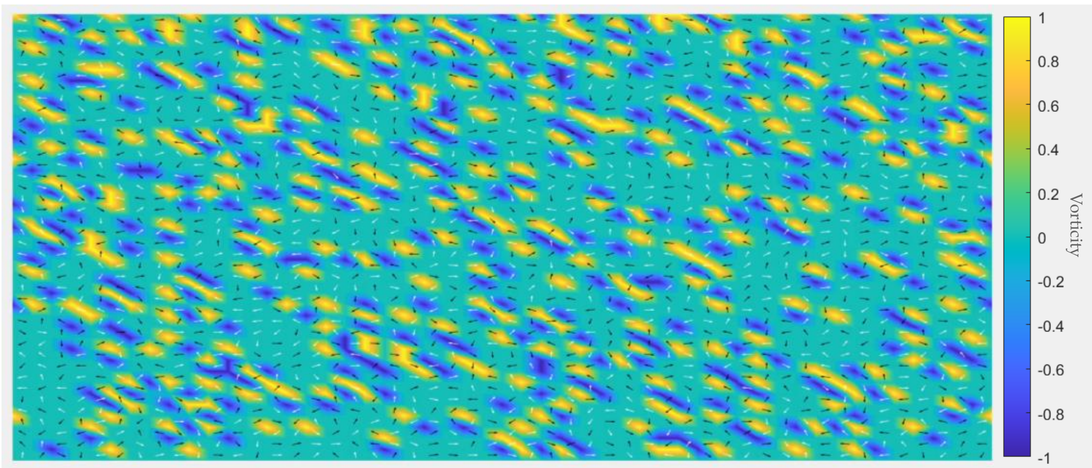
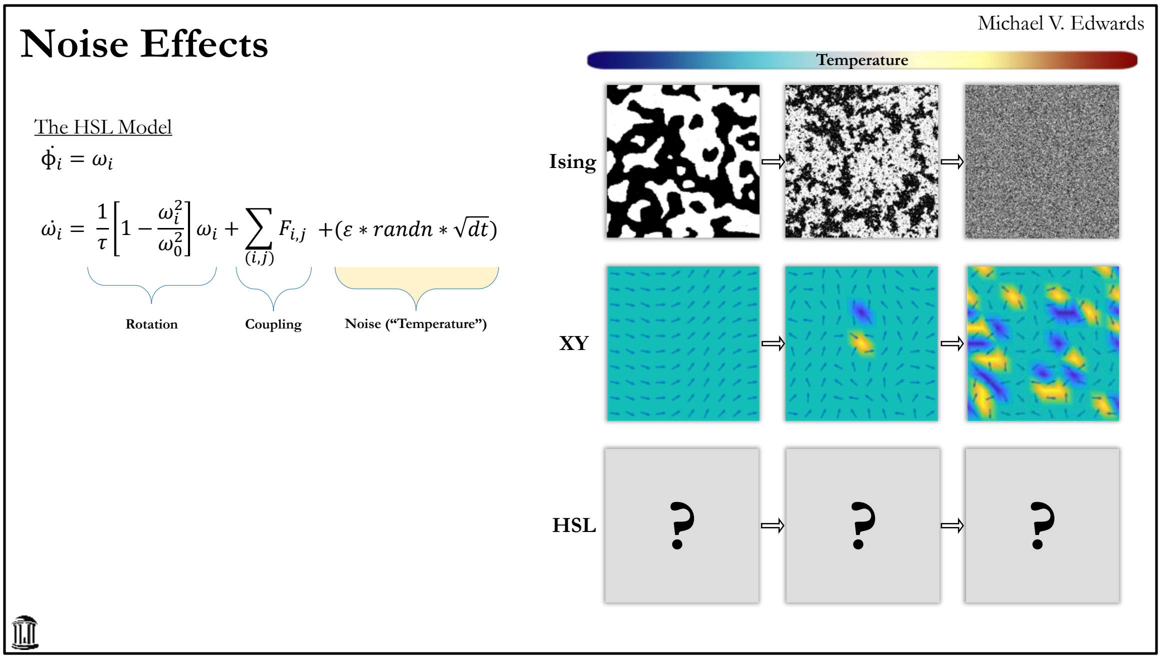
Simulations in 2D

[Periodic Boundaries]



Topological Defects are excitations of particles that resist perturbations

Let's take a look at our model in action, in 2D. You'll see blues and yellows, these are vortices and antivortices, a type of topological defect: excitations of particles that resist perturbations. If a vortex were alone, it would remain in the lattice indefinitely, but since there are many, you will see them annihilate. You will also see black and white arrows. These point in the direction of their phase and visualize the direction of rotation, white for counter-clockwise, black for clockwise. These are random initial conditions, and as we allow the system to equilibrate, you will see that the vortices are removed, and the coupling term begins to create patches of synchronized spins. This process continues, and you will even see a second type of topological defect, the soliton, which is a wave of temporarily reversed spins.



So what do we hope to learn from the HSL Model? Well, there are a number of similar spin lattices, such as the Ising model and the XY model that undergo a phase transition, which is the rapid transition from order to disorder through increasing temperature. The Ising model is limited to spins that are either up or down, and the XY model is limited to the phase of its arrows, which do not have a direction of rotation. We might expect a phase transition in the HSL model on the grounds that it can be defined comparably to the Ising model (counterclockwise vs clockwise) and XY model (phases). To observe these effects, we add a noise term to our equations, which consists of an epsilon that we adjust and two derived terms from a normal distribution.

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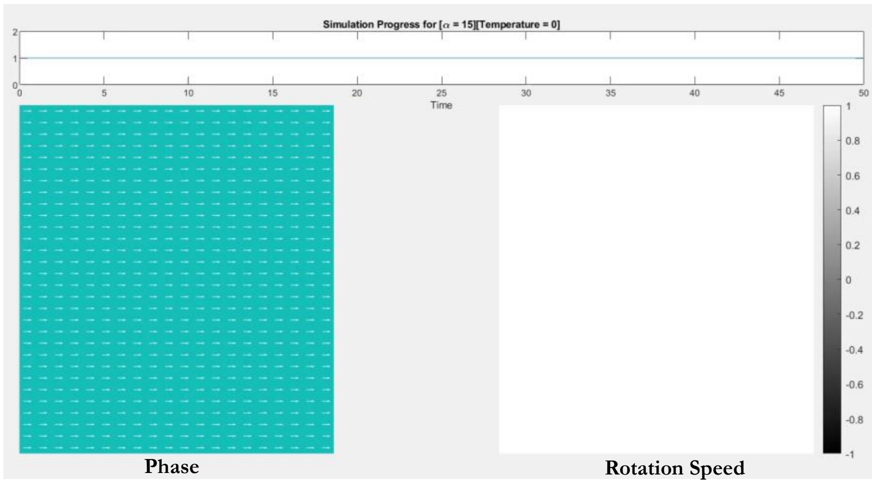
Noise Effect Snapshots

[30x20 Lattice][Aligned Start]



At a temperature of 0, all spins are in alignment. At 8, all spins remain rotating in the same direction, but some variation in the rate of rotation is evident. By 22, a few spins temporarily reverse direction, but the coupling is strong enough to overpower and correct the temperature disruptions. At 26, however, a large number of reversing spins quickly turns to a chain reaction of reversals that ultimately cover the lattice in a unique configuration. If this is a phase transition, we expect this configuration to be random. Is it? Well, if you observe the 'Ising' component, counter-clockwise vs clockwise (especially prominent on the right-hand plot), these spins are obviously random, but if you observe the 'XY' component, the phase, then they are mostly aligned in the direction they point. In fact, these spins are no longer rotating. The influence of high temperature has created a novel form of synchronization.

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Noise Effect Snapshots

[30x20 Lattice][Aligned Start]

- **[ε = 0]:** no variation
- **[0 < ε < 15]:** rotation speeds vary slightly
- **[15 < ε < 24.8]:** spins may flip rotation direction temporarily
- **[ε > 24.8]:** a 'chain reaction' of reversing spins results halts rotation such that phase is ferromagnetic, rotation direction is paramagnetic

*** Temperature does not appear to excite vortices

Here are the results and their corresponding temperature regions.

Prospects

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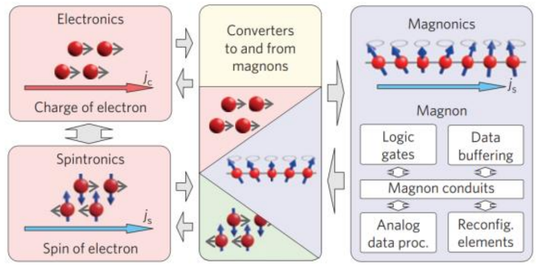
Synchronization

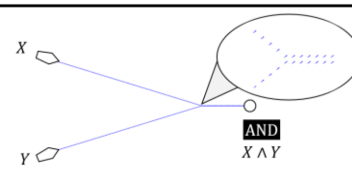
Information Flow



Schematic of Magnon Spintronic System[4]

The AND Gate

X	Y	$X \wedge Y$
0	0	0
0	1	0
1	0	0
1	1	1



Moving forward, before we make any claims of a phase transition, we would like to define an order parameter which captures both the Ising and XY analogs of this system that is not just arbitrary. But this is only half of our recent research. We also want to explore this system as an application of magnon spintronics, which chains spins together for signal transmission. With our durable solitons, we have already used custom geometry to demonstrate a functioning AND gate, and we hope to design more. Modern computer circuitry is held back by electron motion heat dissipation limitations, but as a system that does not involve such charged motion, we hope that our HSL model will guide us to overcoming current technological hurdles.

References

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4. Chumak, A; Vasyuchka, V; Serga, A; Hillebrands, B. Magnon spintronics. Nature Physics. **2015**.