Observation of Quantum-Like Behavior in a Hydrodynamic System

Clayton J. Orback, Tyler A. Onufrak, and Jan L. Chaloupka

Department of Physics & Astronomy, University of Northern Colorado, Greeley CO

Abstract

A pilot-wave hydrodynamic system consists of a small droplet of liquid that is self-propelled across a vibrating bath of similar liquid. The self-propelling nature of the droplet is due to the liquid droplet's own interaction with the waves it generates as it bounces off of the vibrating liquid media surface. By controlling the vibrational frequency of the liquid bath, the small droplet will fail to rejoin the liquid bath and remain as a bouncing droplet above the surface of the bath. The droplet will then continue to produce, and interact with, the waves generated by every subsequent bounce, essentially propelling it across the liquid bath. The self-inducing nature of the system can then be studied under varying conditions and configurations, ultimately serving as an analog to some of the unique phenomena observed in quantum physics. We present results from our hydrodynamic system, including efforts to observe single-particle interference, tunneling, and wave-guide behavior.

References

Single-Particle Diffraction: Y. Couder and E. Fort, "Single-particle diffraction and interference at a macroscopic scale," Physical Review Letters 97, 154101 (2006).

Interference in a Corral: D. M. Harris, J. Moukhtar, E. Fort, Y. Couder, and J. W. M. Bush, "Wavelike statistics from pilot-wave dynamics in a circular corral," Physical Review E 88, 011001(R) (2013).

Double-Slit Interference: A. Andersen, J. Madsen, C. Reichelt, S. R. Ahl, B. Lautrup, C. Ellegaard, M. T. Levinsen, and T. Bohr, "Double-slit experiment with single wave-driven particles and its relation to quantum mechanics," Physical Review E 92, 013006 (2005).

Time Reversal and Information: S. Perrard, E. Fort, and Y. Couder, "Wave-based Turing machine: time reversal and information erasing," Physical Review Letters 117, 094502 (2016).

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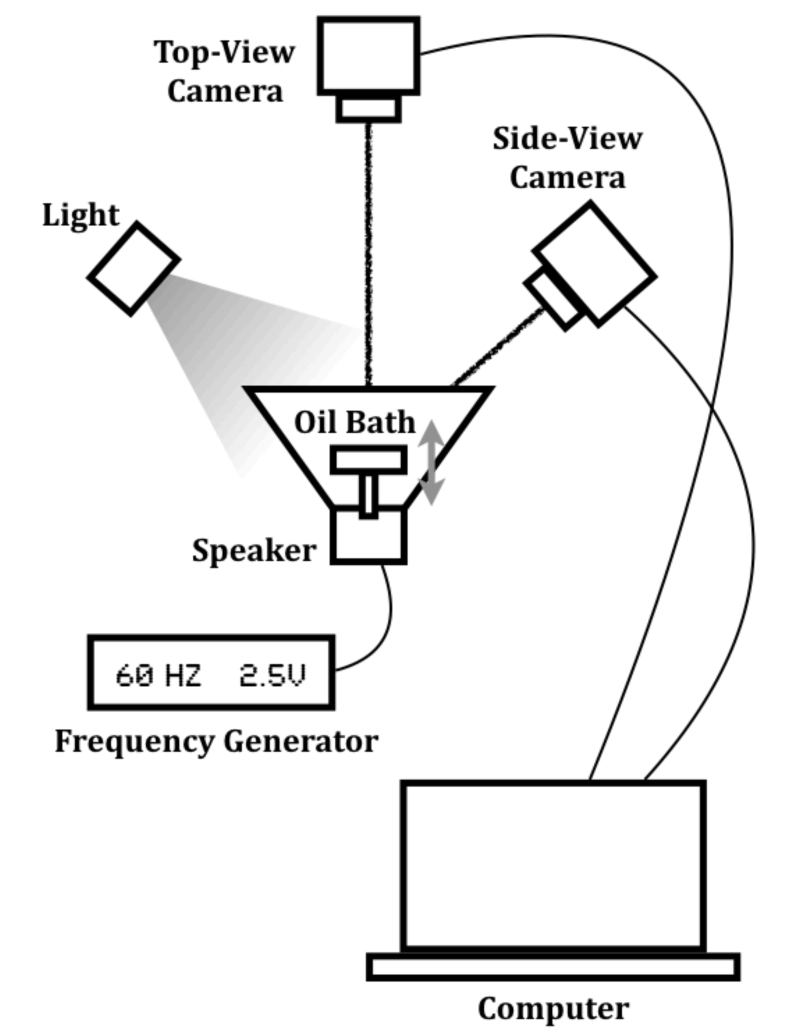
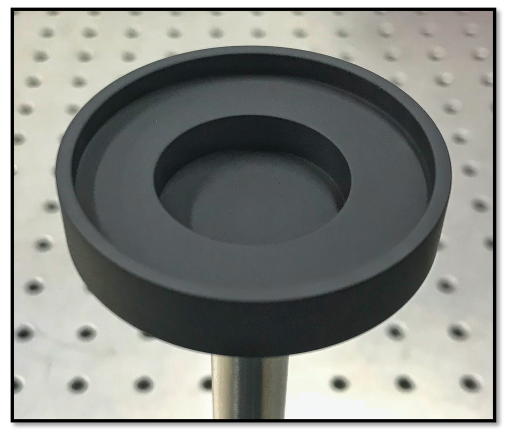
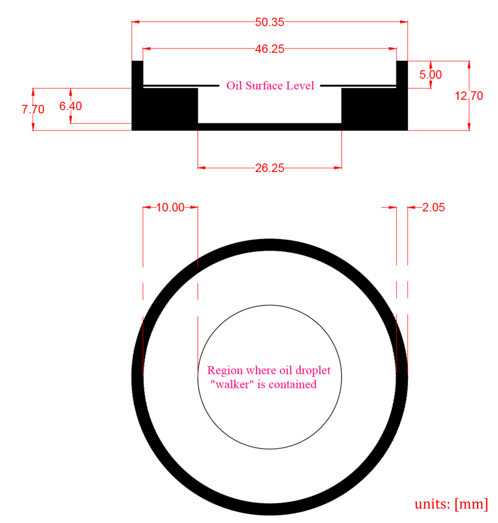
Experimental Setup

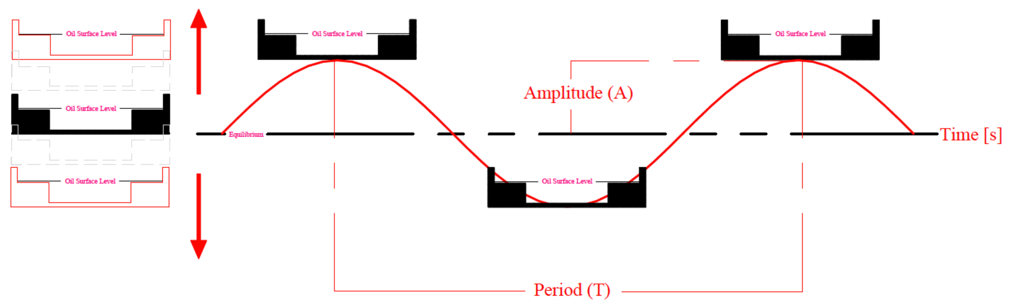


Oil Bath

The oil bath was custom machined out of solid aluminum and mounted to a frequency- and amplitude-controlled speaker. It was painted matte black to limit reflections that would interfere with the droplet tracking software. The bath is filled with silicone oil to a level just above the outer flat region, enabling the bouncing droplet to be contained in the inner region.

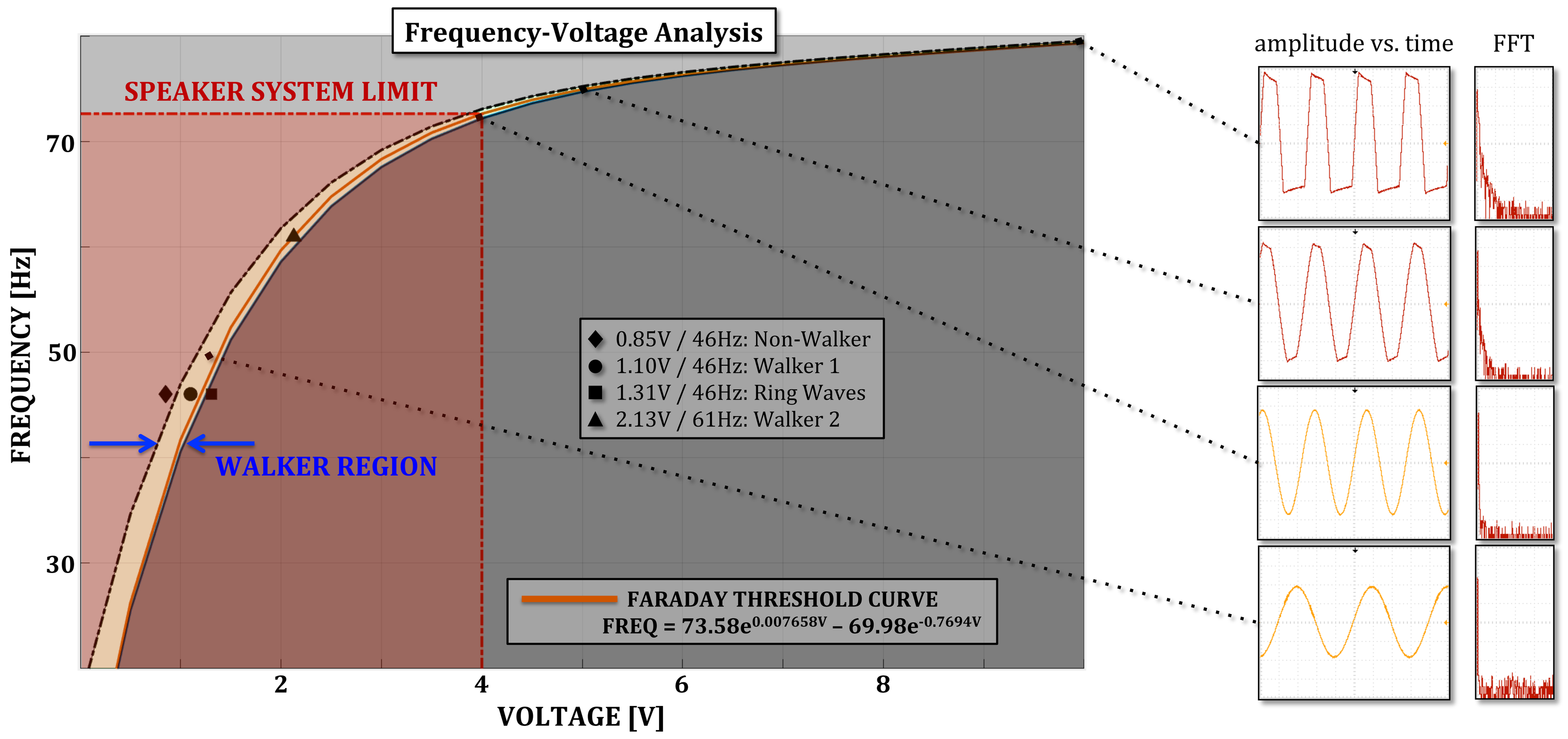




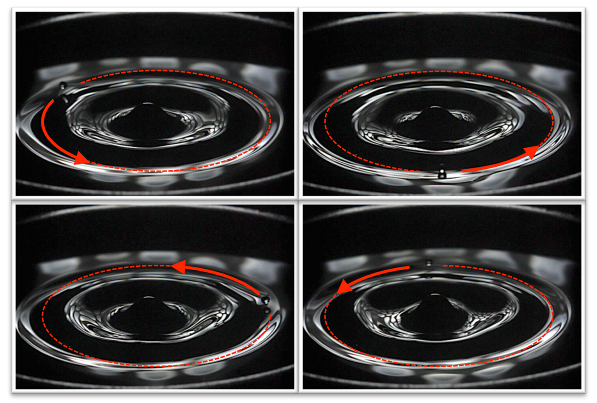


Bouncing Regimes

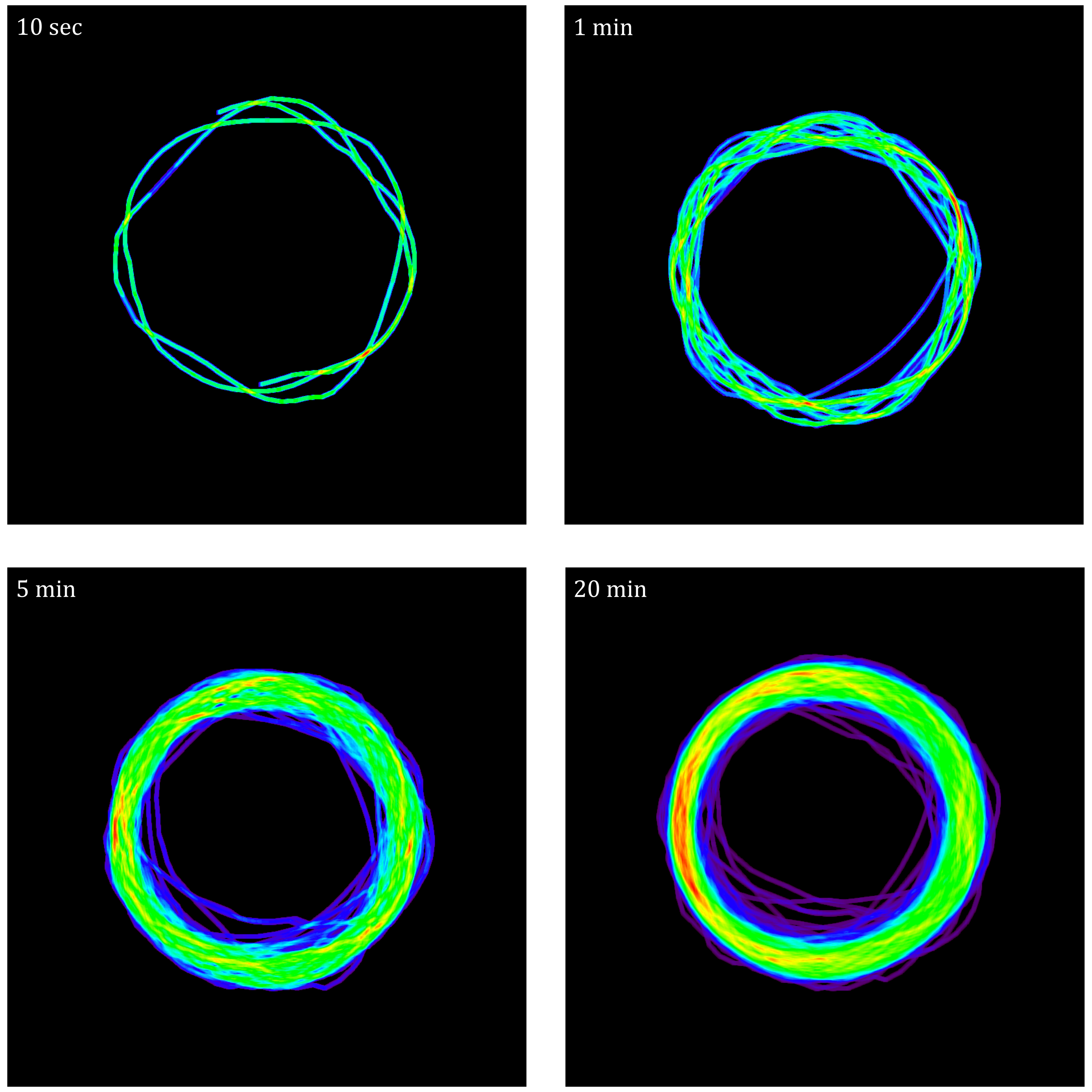
A small, millimeter-scale oil droplet can be made to bounce on the surface of a vibrating oil bath across a wide range of driving frequencies and amplitudes. At low amplitudes, the waves that the droplet generates are too small to influence its motion across the oil surface. At high amplitudes (above the so-called Faraday Threshold), the surface of the oil becomes significantly distorted, and the shape of the bulk surface waves dominates the motion of the droplet. But in a narrow range of amplitudes (the Walker Region below), the droplet exhibits a self-propelled "walking" motion across the flat surface. In this regime, the droplet is a macroscopic, hydrodynamic analog to a quantum mechanical particle and its pilot wave. With our system, we can probe a wide frequency-amplitude range, but we are limited at the very highest frequencies and amplitudes where the speaker motion becomes anharmonic (see the amplitude vs. time and FFT plots below). Ongoing improvements to our speaker system will further extend these frequency-amplitude limits.



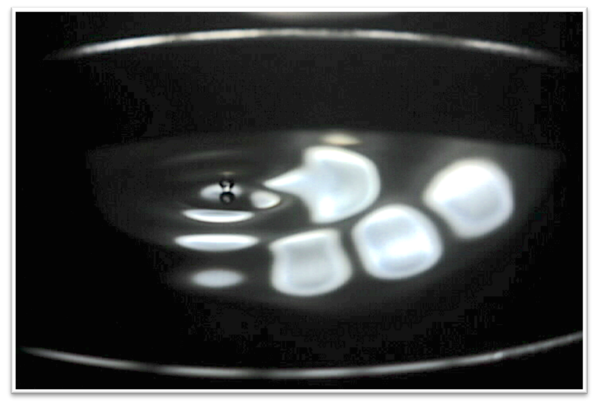
Standing Waves at High Amplitudes



At high oscillation amplitudes, the surface of the oil exhibits significant modulation. By tuning the driving frequency, stable spatial modes can be observed as standing waves. A bouncing droplet in this regime will remain confined within a circular node. The motion is predictable and the pattern generated is the same for all time scales. Frames captured from a side-view video (left) show the circular droplet motion. The top-view droplet tracking system generates "heat maps" of the droplet position for different time scales (below). Bright colors indicate higher droplet "probability density" (due to slower motion or repeated occurrence at a given location).



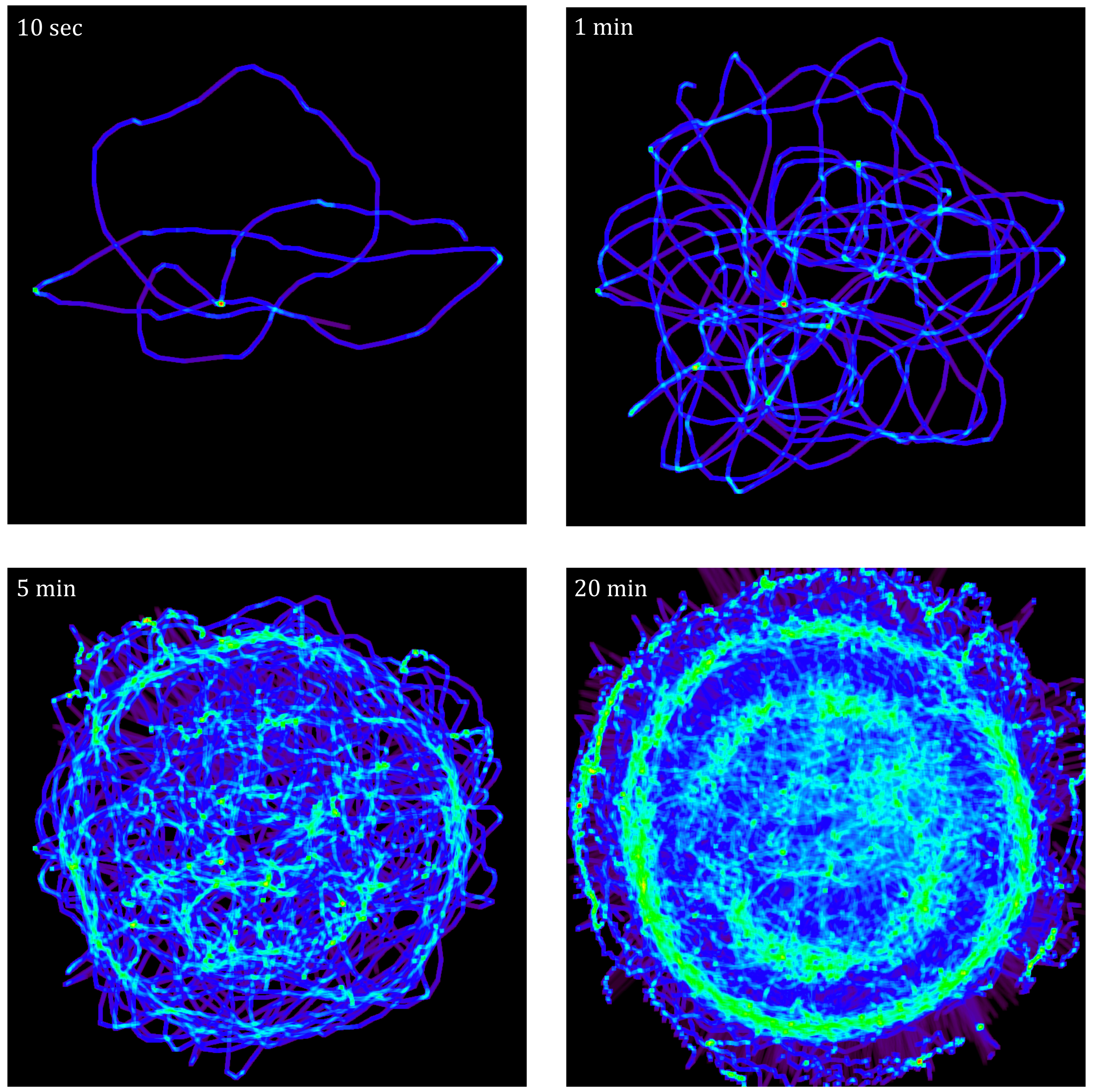
Intermediate Regime



As the oscillation amplitude is reduced, the height of the surface waves inside the oil bath will decrease until they are barely visible (left). As a result, the waves generated by the droplet bouncing on the oil surface will have a greater impact on its subsequent motion. The patterns generated by the motion of the droplet (below) evolve significantly over time, showing evidence of the self-propelled (seemingly random) droplet motion as well as the influence of the (highly structured) standing waves.

Droplet Heat Map Color Scale

← low — Probability Density — high →



Walkers and Interference Effects

Within the narrow "walker region" (see frequency-voltage analysis above), the self-propelled droplets wander across a completely flat oil surface (left). The droplet motion is governed entirely by the waves that the droplet itself creates. For short time scales, this motion exhibits apparently random behavior (below), but for longer times, interference patterns emerge that are completely different from the patterns generated at higher oscillation amplitudes. These patterns are due to the interference of the droplet *with itself!* This behavior is analogous to a single electron trapped in a "quantum corral." The beginnings of a central peak surround by a circular fringe are observed below (denoted by the dashed lines). Ongoing improvements to our speaker system will improve the quality of the observed interference patterns.