Pattern Formations with a Zooplankton:
Experiment and Theory

Anke Ordemann

Frank Moss

Support:

US Office of Naval Research

Alexander von Humboldt Foundation

Motivation:
Vortex-swarming of 'self-propelled' animals

Blue Planet: Seas of Life, Discovery Channel 2001

Outline

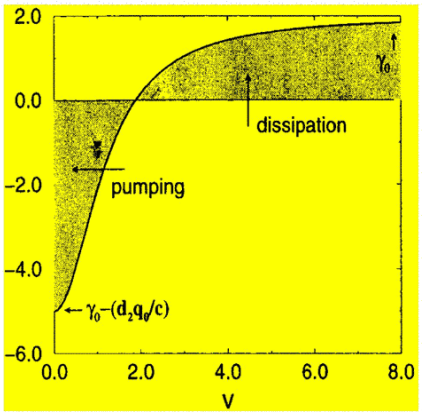
- The Active Brownian Particle (ABP) Theory –
  Erdmann, Ebeling, Schweitzer – Humboldt University Berlin
- Single (few) Particle Motions & Bifurcations
- About *Daphnia* – the experiment
- Random Walk Theory - Measures and Results
- Symmetry Breaking – Vortex motion
- Simulation using RWT
- Summary

Active Brownian Particle (ABP) with internal energy depot

[Schweitzer et al., PRL **80**, 5044 (1998)]

Energy depot: space-dependent take-up $q(\boldsymbol{r})$, internal dissipation $c\,e(t)$, conversion of internal energy into kinetic energy $d_2\,e(t)\,\boldsymbol{v}^2$

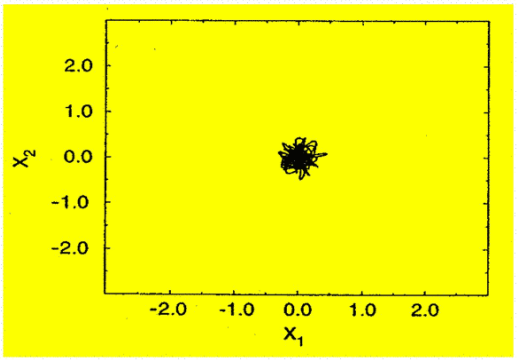
(For uniform distr: $q(\boldsymbol{r}) = q_0$)

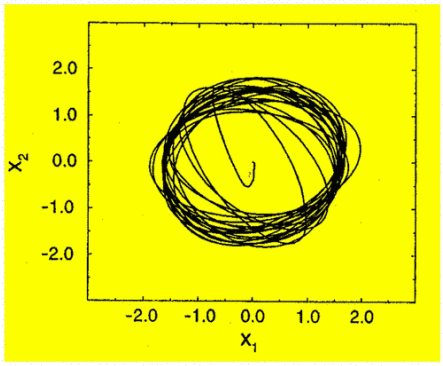


A velocity dependent dissipation

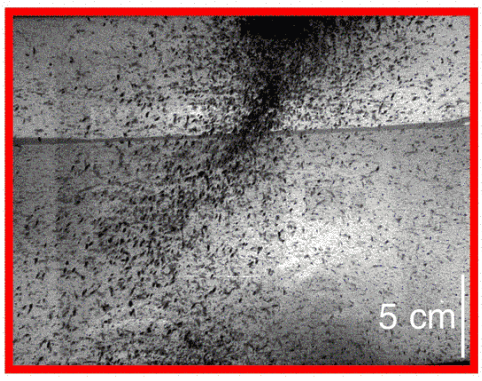
Hopf bifurcation:
Fixed point → limit cycle pair

Bifurcation parameter: —— ——



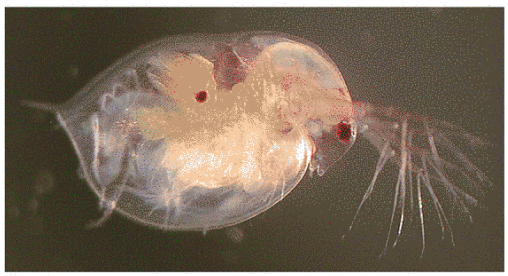


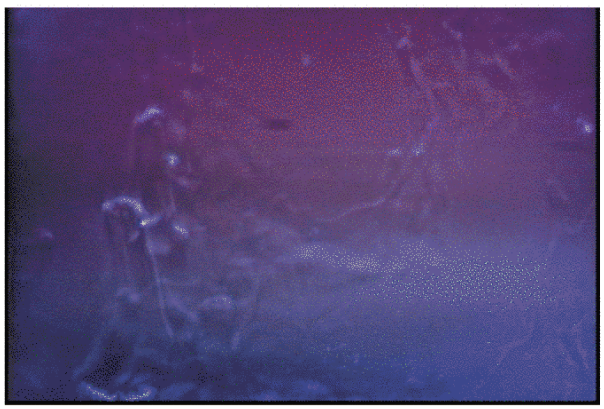
Daphnia make vortices



Side view of vortex-swarming zooplankton *Daphnia* in our lab. Picture by D.F. Russell. ↑

Schlieren technique movie of *Daphnia* motion by Ai Nihongi and Rudi Strickler. →





About *Daphnia*

Daphnia magna, common "water flea".

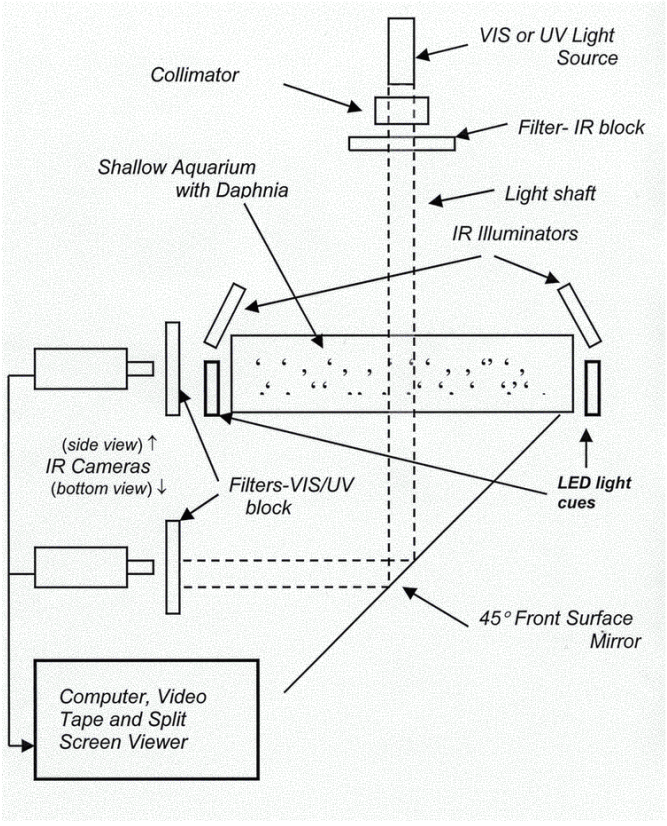
They are:

- ❖Attracted to visible light (VIS)
- ❖Repelled by ultra violet (not used here)
- ❖Blind to infra red (IR)

Record their motions using IR and manipulate motions using VIS

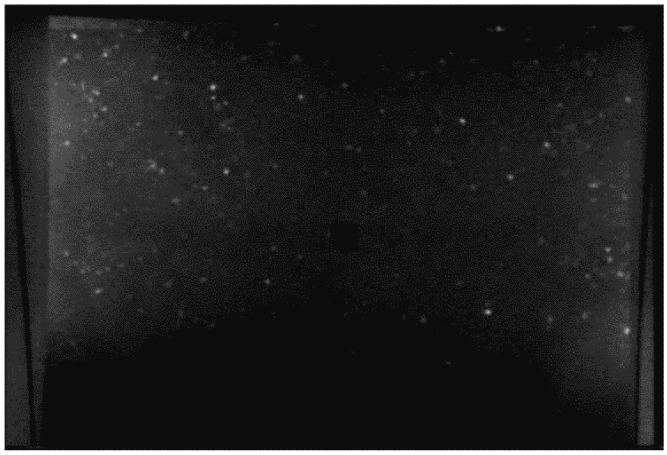
Apparatus

- ❖Side and bottom views recorded simultaneously
- ❖VIS light shaft is the cue
- ❖Illumination and recording in IR

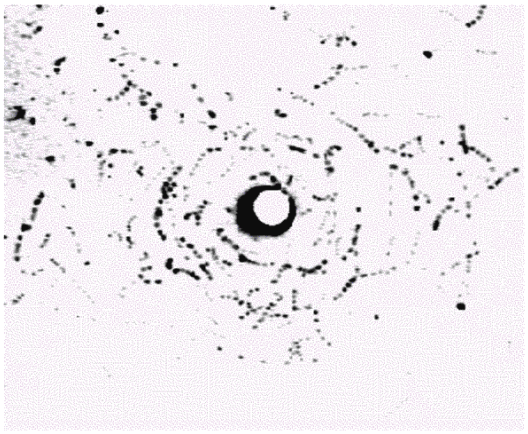


Example Recordings

About 40 animals, approximately equal numbers circling in opposite directions

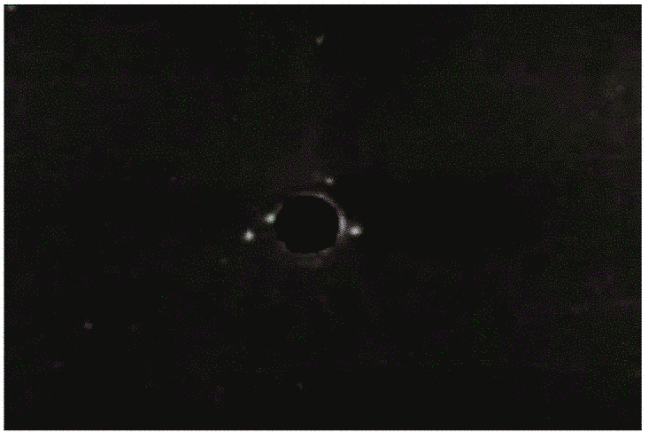


Bottom view of a few *Daphnia* moving around light shaft (radius r =5mm). Movie is speeded up 4 times.

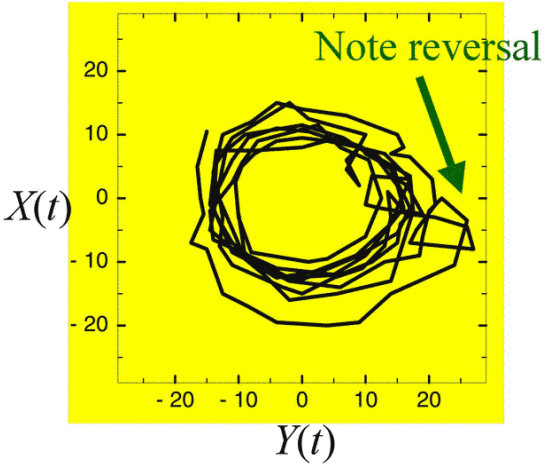


Five successive positions of *Daphnia* taken in intervals of 0.3s (black/white inverted).

Observation of a single *Daphnia*



Bottom view of individual *Daphnia* moving around light shaft. Movie is speeded up 3 times.

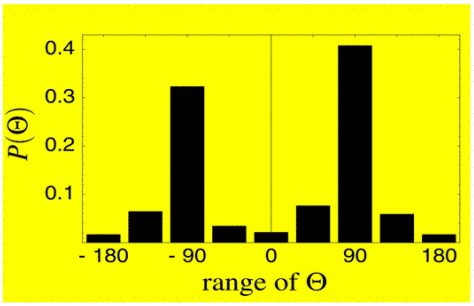


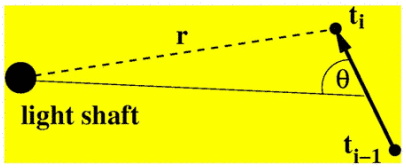
Track of one *Daphnia* individually circling horizontally around light shaft (146s).

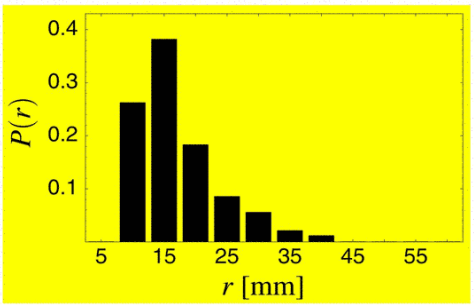
Single *Daphnia* circle individually in both directions around light shaft, frequently changing direction

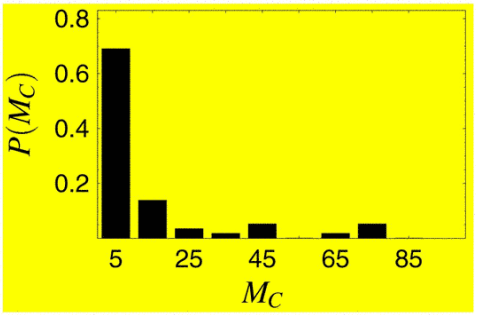
How to characterize observed circular motion?

- M=624 moves from 4 different animals
- Average speed v_{avg} = 5.71 ± 1.35 mm/s









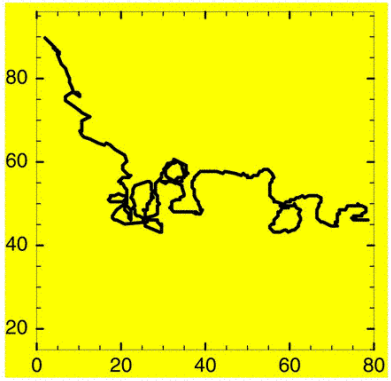
M_C = Number of successive moves before changing direction (CCW vvs CW). $\langle M_C \rangle$ = 11.8

Random Walk Theory - but need

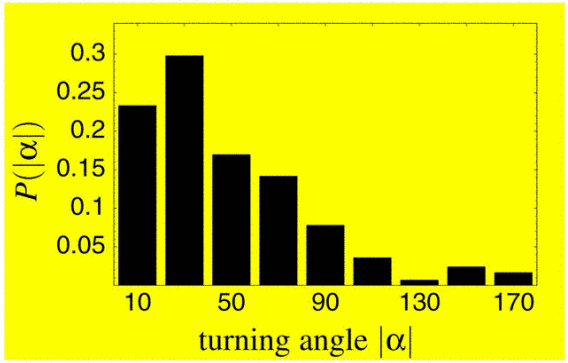
Motion of single *Daphnia* in the **dark.**

1599 moves from 8 different animals

Example track, 200 hops →



Distribution of turning angles, α = directional change after each hop ↓



$P(\alpha)$ symmetric about 0°. $\langle |\alpha| \rangle \cong 35°$

(Similar to oceanic copepods)

Random Walk Theory

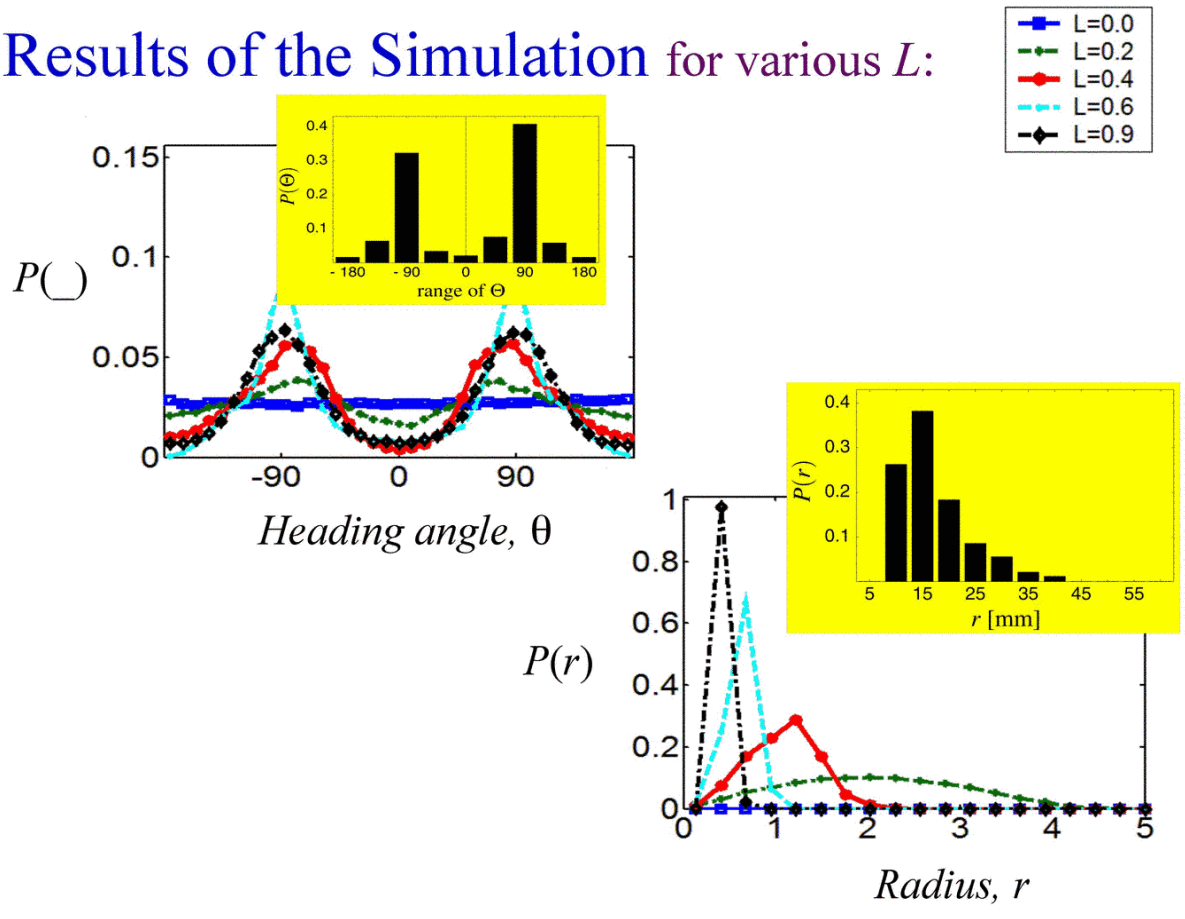
*Short range temporal correlation

*Attraction to light

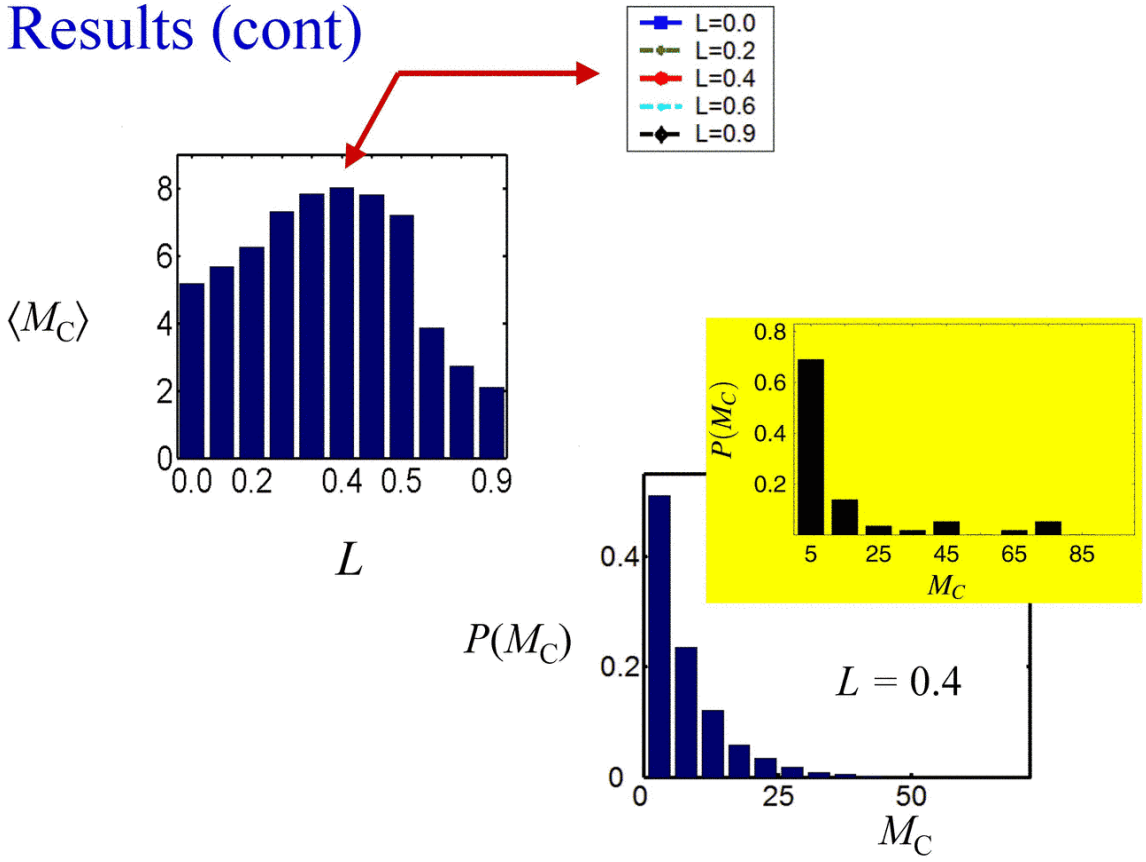
❖*Daphnia* in darkness: At the end of each step, the direction of next time step at t_{i+1} is randomly chosen from observed distribution of turning angle (DTA)

❖*Daphnia* in light field: At the end of each time step, the direction is again chosen from the DTA, but an additional kick of strength $r*L/(L-1)$ towards the light (parabolic potential) is added and the final heading is rescaled to unit length. [$0 \le L < 1$]

Results of the Simulation for various *L*:



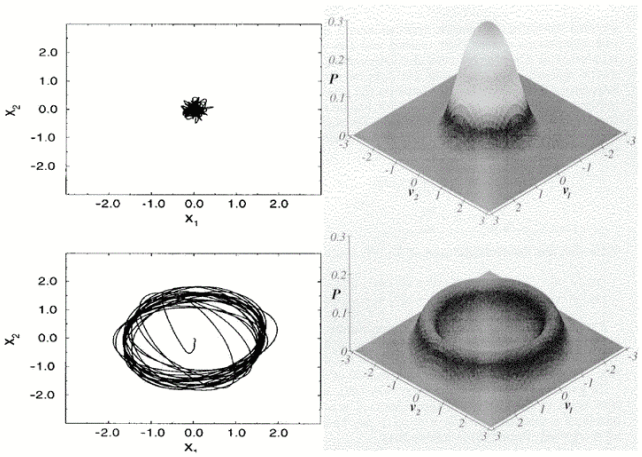
Results (cont)



Many Particle Generalizations - ABP (Humboldt)

Particle-Particle attractive interaction → Mean field potential (ABP) and probability densities of the limit cycle motions.

Symmetric pair of limit cycles.



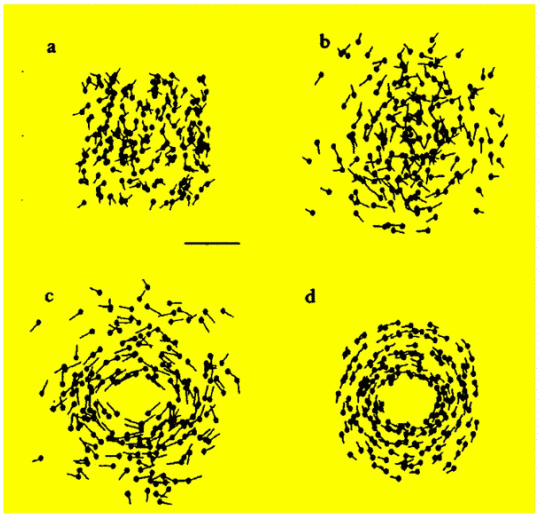
Interacting Active Brownian Particles [Schweitzer *et al.,* PRE **64**, 021110 (2001); Ebeling and Schweitzer, Theory Biosci. **120**, 20 (2001); Erdmann *et al.,* PRE **65**, 061106 (2002)]

Many Particle Generalizations – Levine ⇒

Short range repulsion and long range attraction added to the model of Self-Propelled Interacting Particles [Levine *et al.,* PRE **63**, 017101 (2001)]

Self propelling force, (no alignment)

Self propelling force, (with alignment – range l_c)



Transition to Vortex Motion by a *Daphnia* Swarm

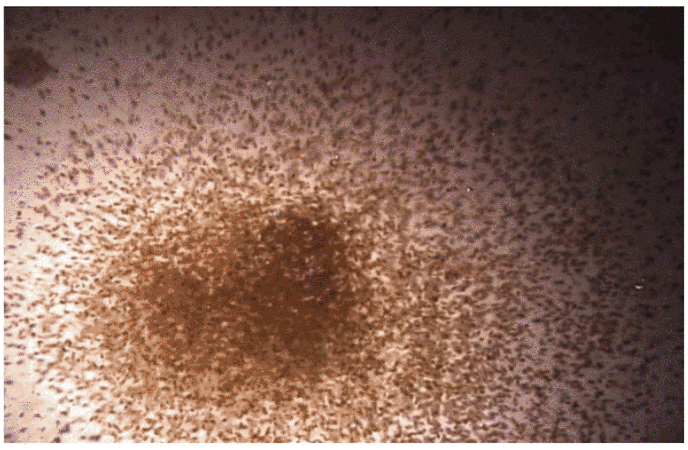
Models: Symmetry of limit cycles must be broken.

Velocity alignment; Avoidance

Daphnia experiment: hydrodynamic coupling likely

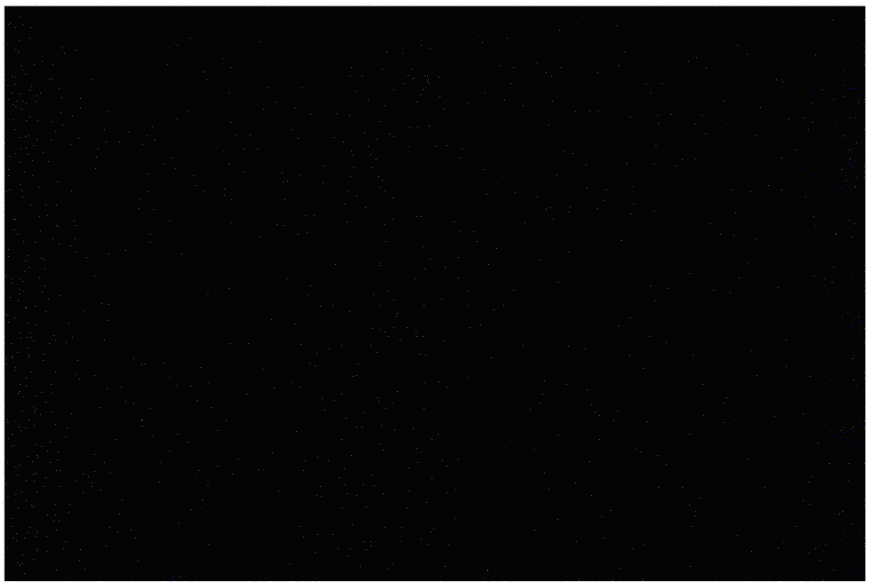
(for birds and fish the alignment is visual with neighbors)

CCW Motion and spiral arms



Another example

CW Motion (after a time delay)

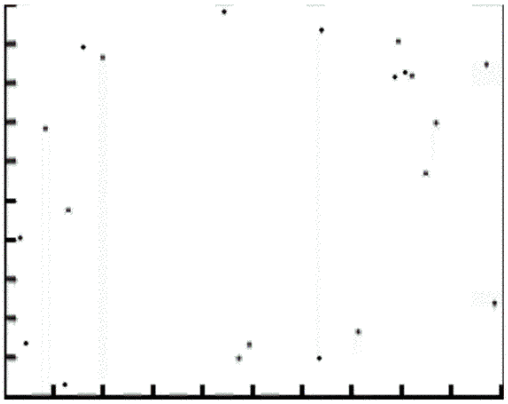


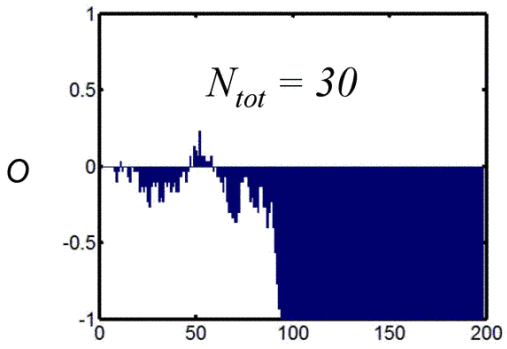
RWT Simulation of the transition: Interacting RW with DTA

- Simple model for (vortex-) swarming *Daphnia*

Indirect inter-agent interactions via water drag are incorporated by adding 'alignment' or 'water drag' kick proportional to:

A local order parameter:





Global order parameter:

$O = (N_{CW} - N_{CCW})/N_{tot}$

Conclusions

Theory predicts four motions:

- ❖Noisy fixed point
- ❖Symmetric pair of limit cycles
- ❖Swarming
- ❖Transition to vortex

All four motions can be observed in experiments with *Daphnia*

Discussion

What are the minimum ingredients that lead to these motions?

A. Few animal (low density) experiments:

- ❖Self-propelled particles (finite non-zero velocity)
- ❖Assigned preference to move in 'forward' direction
- ❖Confinement, arising from Attraction (either as mean field potential from interagent interactions or as external attractive potential)

B. Large animal density experiments:

- ❖In addition to the above – a symmetry breaking (velocity alignment) mechanism.