Active nematics at interfaces

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Outline

• Introduction: Active systems/Active matter

• Active nematics in contact with passive oils
  (indirect measure of the active nematic viscosity)

• Active nematics in contact with smectic LCs
  (taming and steering active flows)

• Active droplets emulsified in oil and nematic LCs
  (coupling defects of active and passive liquid crystals)
Active systems/Active matter: Introduction

Active systems are ensembles of autonomous units showing collectively organized behavior.

Active matter is a fascinating emerging area in the field of non-equilibrium Condensed Matter Physics.

Unifying characteristics: active matter systems are composed of self-driven units, active particles, each capable of converting stored or ambient free energy into systematic movement.

The interaction of active particles which each other and with the medium they live in, gives rise to highly correlated collective motion.

- Active soft matter, M. C. Marchetti et al., Rev. Mod. Phys. 85, 1143 (2013)
Active matter: Living realizations

In vitro cell extracts of biofilaments and motor proteins

FIG. 2. Patterns organized in vitro by the action of multimeric kinesin complexes on microtubules, imaged by dark-field microscopy. The concentration of motor proteins increases from left to right. (a) A disordered array of microtubules. The other two images display motor-induced organization in (b) spiral and (c) aster patterns. The bright spots in the images correspond to the minus end of microtubules. These remarkable experiments from Surrey et al. (2001) led the way to the study of pattern formation in active systems. Adapted from Surrey et al., 2001.

Physical Properties Determining Self-Organization of Motors and Microtubules

Thomas Surrey, François Nédélec, Stanislas Leibler, Eric Karsenti

SCIENCE VOL 292 11 MAY 2001 1167
Active matter: Living realizations

Cilia and flagella

The surface of ciliated protozoa, such as Paramecium cells, is covered with a dense array of cilia. Ciliary movements exhibit beautiful metachronal wave-like coordination where a constant phase difference is maintained between adjacent cilia.

Cilia-Like Beating of Active Microtubule Bundles

Timothy Sanchez, David Welch, Daniela Nicastro, Zvonimir Dogic

22 JULY 2011  VOL 333  SCIENCE
Active matter: Living realizations

Cell tissues

Fig. 8. A $m = -1/2$ disclination is shown for melanocytes. The bar is 100 μm. Different possibilities are shown: (a) the core of the disclination is an area free of cells. (b) The core of the disclination is an area with isotropically distributed cell. (c) The core of the disclination is occupied by a star-shaped cell. The cells which form the nematoid fluid are in an elongated bipolar state.


Elastic properties of nematoid arrangements formed by amoeboid cells

R. Kemkemen, D. Kling, D. Kaufmann, and H. Gruler
Volvox was once described as "the first multicellular plant." Now it is generally thought of as a colony of algae cells that have made a sort of "long-term commitment".

A dense group of E. coli swims in the roughly two dimensional space at an air water interface. Their collective motion is significantly different from their motion as single cells. Under these conditions they behave more like an active fluid.

Video courtesy Matthew Copeland, University of Wisconsin, Madison.
Active systems: Living realizations

Flocking birds/Fish schools

**Fig. 1.** (A) 2D projection of the velocities of the individual birds within a starling flock at a fixed instant of time (flock 26-10, 1,246 birds, linear size L = 36.5 m). Vectors are scaled for clarity (see Dataset S1 for original data). The flock is strongly ordered and the velocities are all aligned. (B) 2D projection of the individual velocity fluctuations in the same flock at the same instant of time (vectors scaled for clarity). The velocity fluctuation is equal to the individual velocity minus the center of mass velocity, and therefore the spatial average of the fluctuations must be zero. Two large domains of strongly correlated birds are clearly visible. (C) Normalized probability distribution of the absolute value of the individual velocities and of the absolute value of the velocity fluctuations (same flock as in A and B). The velocity fluctuations are much smaller in modulus than the full velocities.

**Starlings on Otmoor (near Oxford)**

**Scale-free correlations in starling flocks**

Andrea Cavagna\textsuperscript{a,b,1}, Alessio Cimarelli\textsuperscript{b}, Irene Giardina\textsuperscript{a,b,1}, Giorgio Parisi\textsuperscript{b,c,d,1}, Raffaele Santagati\textsuperscript{b}, Fabio Stefanini\textsuperscript{b,2}, and Massimiliano Viale\textsuperscript{a,b}

PNAS | June 29, 2010 | vol. 107 | no. 26 | 11865-11870

**Sardine run (South Africa)**
Active systems: Human-scale realizations

Human gatherings

*Catalonian National Day 2014 (Barcelona)*
...... *but also 2012-2016*
Vibrated granular matter

Fig. 1. Giant number fluctuations in active granular rods. (A) A snapshot of the nematic order assumed by the rods. There are 2820 particles (counted by hand) in the cell (area fraction is 66%) being sinusoidally vibrated perpendicular to the plane of the image, at a peak acceleration of $\Gamma = 5$. The sparse region at the top between 10 and 11 o'clock is an instance of a large density fluctuation. These take several minutes to relax and form elsewhere. (B) The magnitude of the number fluctuations (quantified by $\sqrt{\bar{N}}$ and normalized by $\sqrt{N}$) against the mean number of particles, for subsystems of various sizes. The number fluctuations in each subsystem are determined from images taken every 15 s over a period of 40 min (26). The squares represent the system shown in (A). It is a dense system where the nematic order is well developed. The magnitude of the scaled number fluctuations decreases in more dilute systems, where the nematic order is weaker (SDM text). Deviations from the central limit theorem result are still visible at an area fraction ≈ 58% (diamonds) but not at an area fraction ≈ 35% (circles). (Inset) The nematic-order correlation function as a function of spatial separation.

Long-Lived Giant Number Fluctuations in a Swarming Granular Nematic

Vijay Narayan, Sriram Ramaswamy, Narayan Menon

SCIENCE VOL 317 6 JULY 2007

Flocking at a distance in active granular matter

Nitin Kumar, Harsh Soni, Sriram Ramaswamy & A.K. Sood

Millimetre-sized tapered rods rendered motile by contact with an underlying vibrated surface and interacting through a medium of spherical beads
Active matter: Non-living realizations

Motile colloids

Emergence of macroscopic directed motion in populations of motile colloids

Antoine Bricard, Jean-Baptiste Caussin, Nicolas Desreumaux, Olivier Dauchot & Denis Bartolo

7 November 2013 | Vol 503 | Nature | 95

Quincke roller
Active matter: Non-living realizations

Motile colloids

Catalytic Nanomotors: Autonomous Movement of Striped Nanorods
Walter F. Paxton,† Kevin C. Kistler,† Christine C. Olmeda,† Ayushman Sen,,*†
Sarah K. St. Angelo,† Yanyan Cao,† Thomas E. Mallouk,*,† Paul E. Lammert,‡ and
Vincent H Crespi*,‡
13424 = J. AM. CHEM. SOC. 2004, 126, 13424–13431

Living Crystals of Light-Activated Colloidal Surfers
Jeremie Palacci,1* Stefano Sacanna,3 Asher Preska Steinberg,2 David J. Pine,† Paul M. Chaikin†

Stimuli-Responsive Microjets with Reconfigurable Shape**
Veronika Magdanz, Georgi Stoychev, Leonid Ionov,* Samuel Sanchez,* and Oliver G. Schmidt
Angew. Chem. 2014, 126, 2711 –2715
Active matter: Non-living realizations

Electrophoretic colloids dispersed in LCs

DOI: 10.1002/anie.201406136

Reconfigurable Swarms of Nematic Colloids Controlled by Photoactivated Surface Patterns**
Sergi Hernández-Navarro, Pietro Tierno, Joan Anton Farrera, Jordi Ignés-Mullol, and Francesc Sagués

Active nematic

Depletion force (PEG)

Kinesin motor complex (ATP-fueled)

microtubules

Oil

Water

Active nematic

- Active 2d nematic liquid crystal
Active nematic
Active nematics in contact with passive oils
(indirect measure of the active nematic viscosity)
Open cell design

Air
oil
W (+ Pluronic/surfactant)

Ø 5mm

PolyAcrylamide-coated substrate
2d active nematic
PDMS block
Viscous damping

\[ 5 \times 10^{-3} \text{ Pa} \cdot \text{s} \quad 0.05 \text{ Pa} \cdot \text{s} \quad 0.5 \text{ Pa} \cdot \text{s} \quad 5 \text{ Pa} \cdot \text{s} \quad 300 \text{ Pa} \cdot \text{s} \]

oil viscosity $\uparrow$

\[ 0.05 \text{ Pa} \cdot \text{s} \quad 5 \text{ Pa} \cdot \text{s} \quad 300 \text{ Pa} \cdot \text{s} \]
Quantitative measurements: Speed and density of defects
Defect creation rate \( R_c \sim (\ell_\alpha^2 \tau)^{-1} \)

active length scale \( \ell_\alpha = \sqrt{K/|\alpha|} \)

time scale for active distortions \( \tau = \gamma/|\alpha| \)

Defect annihilation rate \( R_\alpha \sim \sigma v n^2 \)

effective cross section for defect annihilation \( \sigma \)

At steady state \( v n^2 \sim \alpha^2 / (\gamma \sigma K) \)
For constant ATP concentration and assuming elastic constant and rotational viscosity do not change

\[ vn^2 \sim constant \]
Alternatively, taking into account variable defect core size

\[ \xi_Q \sim K^{1/2} \]

suggesting that core size and cross section are independent length scales
Calculation of the velocity of a +1/2 defect

Hydrodynamics of a thin (incompressible) active film confined between to bulk fluids.

\[ \eta_i \nabla_i^2 u_i - \nabla p_i = 0 \]

Stokes equations

\[ \eta_N \nabla_{||}^2 u_{||} - \nabla_{||} p + \hat{n} \cdot (\sigma_o - \sigma_w) + \nabla_{||} \cdot \sigma_a = 0 \]

Active stress

\[ \sigma_a = \alpha Q \]

In plane velocity

\[ u_{||}(\mathbf{k}) = G(k) \mathcal{P}f(k) \]

\[ f(k) = \int e^{-i\mathbf{k} \cdot \mathbf{r}} \nabla_{||} \cdot \sigma_a \]

\[ \mathcal{P} = I - \mathbf{k}\mathbf{k}/k^2 \quad \text{transverse projection operator} \]

Green function

\[ G(k) = \frac{1}{\eta_N k^2 + k \left[ \eta_o \tanh(kd_o) + \eta_w \coth(kd_w) \right]} \]

\[ d_o, d_w \quad \text{oil, water layer depths } \sim 1\text{mm} \]
Force distribution created by a +1/2 defect at the origin

\[ f(r) = \alpha \nabla \cdot Q \]
\[ Q = S \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \]

in polar coordinates

\[ f(r) = |\alpha| \left( \frac{dS}{dr} + \frac{S}{r} \right) \hat{e}_x \]

classical solution

\[ S(r) \approx r / 2\xi_Q \]

\[ f_x = |\alpha| / \xi_Q \text{ for } r < \xi_Q \text{ and } f_x = |\alpha| / r \text{ for } r > \xi_Q \]
Identifying $d_o$ and $d_w$ ($d_o \sim d_w = d$) taken as large length scales of the system, we can approximate the Green functions

$$G(k) \simeq G_>(k) = \frac{1}{\eta_N k^2 + \eta_o k} , \quad \text{for} \quad kd \gg 1 ,$$

$$G(k) \simeq G_< (k) = \frac{1}{(\eta_N + \eta_o d)k^2 + \eta_w/d} = \frac{1}{\eta_R (k^2 + \ell_\Gamma^{-2})} , \quad \text{for} \quad kd \ll 1$$

in terms of

renormalized viscosity $\eta_R = \eta_N + \eta_o d$

frictional screening length $\ell_\Gamma = \sqrt{\eta_R d/\eta_w}$
Calculation of the defect velocity is split with a cutoff at small distances given by defect core size (we do not expect hydrodynamic description to be valid inside) and at large distances in terms of the lateral dimension \(L\) (\(L \sim 5\ mm\))

\[
u_0 = u_+ + u_-
\]

\[
u_+ = \frac{1}{2} \int_0^L \, d^2r \, G_+(r) \frac{\alpha}{r} = \frac{\alpha \ell_T}{\eta_R} \mathcal{F}_+(\frac{L}{\ell_T}, \frac{d}{\ell_T})
\]

\[
u_- = \frac{1}{2} \int_{\xi_Q}^{d} \, d^2r \, G_-(r) \frac{\alpha}{r} = \frac{\alpha |d|}{\eta_N} \mathcal{F}_-(\frac{\eta_0 d}{\eta_N}, \frac{d}{\xi_Q})
\]

scaling functions read

\[
\mathcal{F}_+ \left( \frac{L}{\ell_T}, \frac{d}{\ell_T} \right) = \int_{d/\ell_T}^{L/\ell_T} \, dx \, K_0(x),
\]

\[
\mathcal{F}_- \left( \frac{\eta_0 d}{\eta_N}, \frac{d}{\xi_Q} \right) = \frac{\pi}{2} \int_{\xi_Q/d}^1 \, dx \left[ H_0 \left( \frac{\eta_0 d}{\eta_N} x \right) - Y_0 \left( \frac{\eta_0 d}{\eta_N} x \right) \right]
\]

in terms of (modified) Bessel and Struve functions
In the limit $\eta_0 d / \eta_N \ll 1$ and $d / \xi_Q \gg 1$ ($\xi_Q \sim 10\mu m$)

$$
\begin{align*}
    u_\lt & \simeq \frac{|\alpha|}{\eta_N} \frac{\ell_\Gamma}{\ell_\Gamma} \mathcal{F}_\lt \left( \frac{L}{\ell_\Gamma}, \frac{d}{\ell_\Gamma} \right), \\
    u_\gt & \simeq \frac{|\alpha|}{\eta_N} \left\{ 1 + \ln \left( \frac{2\eta_N}{\eta_0 d} \right) - \frac{\xi_Q}{d} \left[ 1 + \ln \left( \frac{2\eta_N}{\eta_0 \xi_Q} \right) \right] \right\}
\end{align*}
$$

with $L / \ell_\Gamma \sim d / \ell_\Gamma \ll 1$

very small and oil viscosity independent

Finally, thus

$$
u_0 \simeq u_\gt$$
Two-dimensional active nematic viscosity

$$\eta_N = 13(\pm5) \times 10^{-3} \text{ Pa s m}$$

$$|\alpha| = 1 - 10 \times 10^{-5} \text{ Pa m}.$$ 

both quantities can be converted to 3d effective values by using the thickness of the nematic layer ($\sim 0.2\mu m - 2\mu m$)
It could be argued that this calculation does not hold in the case of many defects. One may extend this calculation by replacing $d$ by the mean defect separation $\ell_d = n^{-1/2}$

$$u_0 \simeq \frac{|\alpha|\ell_d}{\eta_N} F_\eta \left( \frac{\eta_0 \ell_d}{\eta_N} , \frac{\ell_d}{\xi_Q} \right)$$

$$\eta_N \sim 6.5 - 13 \times 10^{-4} \text{ Pa s m}$$
Active turbulence in 2d nematic

Okubo-Weiss parameter

\[ OW = (\partial_x v_x)^2 + (\partial_y v_x)(\partial_x v_y) < 0 \]

Exponential distribution

length scale identified as \( l_\alpha \) from numerical simulations

*L. Giomi et al., PRX 5, 031003 (2015)*
Active nematics in contact with passive liquid crystals
(taming and steering active flows)
8CB liquid crystal

4-cyano-4’-octylbiphenyl

\[ \text{Cr} \leftrightarrow \text{SmA} \leftrightarrow \text{N} \leftrightarrow \text{I} \]

NEMATIC phase

SMECTIC-A phase
8CB: Nematic phase

Air
NLC
W (+ Pluronic surfactant)

Nematic

LC

2d active nematic

PolyAcrylamide-coated substrate

PDMS block

Ø 5mm
8CB: Smectic phase

Active nematic is trapped/scattered
8CB: Smectic phase

Power law distribution: from exponential to scale free

**Taming active turbulence**
8CB
Focal conic domains

4-cyano-4’-octylbiphenyl

$\text{Cr} \longleftrightarrow \text{SmA} \longleftrightarrow \text{N} \longleftrightarrow \text{I}$

Air

8CB

W (+ surfactant)

50 µm
8CB
Focal conic domains

4-cyano-4'-octylbiphenyl

\[ \text{Cr} \rightleftharpoons 21.4^\circ C \quad \text{SmA} \rightleftharpoons 33.4^\circ C \quad N \rightleftharpoons 40.4^\circ C \quad \text{I} \]

Air

8CB

W (+ surfactant)
8CB
Focal conic domains

4-cyano-4’-octylbiphenyl

Anisotropic viscosity
- Flow is favored along the smectic planes
- Radial flow is hindered!

Air

<table>
<thead>
<tr>
<th>8CB</th>
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W (+ surfactant)
Superimposed images of fluorescence and reflection confocal microscopies
Influence of material parameters

Decreasing ATP concentration by a factor 10
Changing the threshold for trapping by tuning parameters of the active nematic: activity (ATP concentration) and stiffness (PEG contents)
Scenarios for defect creation and annihilation

Topological charge = +1

Scale bar, 50μm
Bend-like instability of aligned microtubules
Tracking flows in active and passive phases simultaneously
$T^\uparrow \quad T^\downarrow, \vec{B}$

SmA $\rightarrow$ N $\rightarrow$ SmA

SmA

25 °C

500 μm
8CB: *bookshelf* geometry

Applied magnetic field 4kG
8CB: bookshelf geometry

**Anisotropic viscosity**
- Flow is favored along the smectic planes
  - \( \perp \) to \( \vec{B} \)
Tuning active nematic alignment
Organization based on lanes of antiparallel flows separating bands of aligned MT bundles

P. Guillamat et al., *Control of active liquid crystals with a magnetic field*, *PNAS 113*, 5498-5502 (May 2016)
(highlighted in Nature Reviews Materials, 24 May 2016)
Instability of aligned active nematic

- Structure and dynamics

Bending instability
• Structure and dynamics
• Structure and dynamics
• Structure and dynamics

Reflection confocal microscopy
• speed vs $|\alpha| = \ln[ATP]$

\[ \tau = \frac{\gamma}{|\alpha|} \]

In a turbulent active nematic $\rightarrow$ speed $\sim |\alpha|^{1/2}$

- lane spacing vs $|\alpha|$

\[ l_\alpha = \sqrt{\frac{K}{|\alpha|}} \]

\[ l^2 \sim \alpha \]
Active nematic droplets emulsified in nematic LCs
(coupling defects of active and passive liquid crystals)

Inspired by (dedicated to) the Ljubljana group
Active gels in spherical confinement

Active vesicles


- 4 (+1/2) defects
- Planar→Tetrahedric transition-
- Characteristic frequency
Active droplets in isotropic oils

- \( R > R^* \sim 50 \mu m \rightarrow -1/2 \) defects
  - CHAOTIC DEFECT DYNAMICS

- \( R < R^* \rightarrow 4 +1/2 \) defects
  - PERIODIC PATTERNS
Active droplets in 5CB (nematic)

- Planar anchoring
  - Pluronic F127
  - Boojums

- Homeotropic anchoring
  - TWEEN 80 or DSPE-PEG
  - SRs (and boojums)
Distorted SR
no symmetry

**Oscillating SR**
quadrupolar symmetry?

Folded SR
(hyperbolic point defect)
dipolar symmetry
• [ATP]=140 µM
• [ATP]=1400 µM
The primary bend instability.....

Detecting the primary bend instability of extensible systems

......in cascade
Conclusions

Active nematic flows can be effectively conditioned/actuated through fluid interfaces

• Interfacing with isotropic oils at flat interfaces permits to evaluate an active nematic viscosity
• Interfacing with passive smectic LCs unveils an strategy of control/steering of active flows
• When encapsulated in droplets dispersed in nematic LCs we observe interesting effects of coupled dynamics of active and passive defects
Acknowledgments

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Hydrodynamic model: S. Shankar, M. C. Marchetti (Syracuse University)

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Z. Dogic and S. DeCamp (Brandeis University Materials Research Science)
Hallbach Array

- Uniform magnetic field
  - 0.4T
**8CB**: Parabolic FCD
8CB rheology measurements

- $8CB_{SmA}$ (T=25 °C)
- $8CB_N$ (T=37 °C)

$\mu = 30 \pm 3 \text{ mPa}\cdot\text{s}$

Thermo Haake RheoStress 1 rheometer, in constant stress mode, using cone-plate geometry with a 1°, 60 mm diameter titanium cone.