Defect dynamics of active nematics and rheology of isotropic gels
Basic building blocks of active nematics

- microtubules
  - long rigid filaments
  - stabilized with GMPCPP

- depletion induced MT bundling
  - non-adsorbing polymer (PEG) induced effective attractive interactions which lead to MT bundling

- molecular motor kinesin
  - motors convert energy from ATP hydrolysis into movement along MT backbone
Bundle geometry greatly increases filament sliding efficiency

MT sliding depends on relative filament polarity !!!

- **polar MT bundle**  
  - no interfilament sliding
  
  biotin labeled kinesin are Bound into clusters via Tetrameric streptavidin.

- **anti-polar MT bundle** – motor driven filamentsliding
  
  passive MT bundles – diffusive interfilament sliding

- bundle geometry greatly increases filament sliding efficiency
- MT sliding depends on relative filament polarity !!!
dynamics of isolated extensile MT bundles

- isolated MT bundles are static indicating polarity sorting
- bundle recombination reinitializes local polarity sorting
Active Nematic liquid crystals

Topological defects

$\frac{1}{2}$ and $-\frac{1}{2}$ disclinations indicate nematic order
disclination defects in equilibrium nematics

topological charge $Q = +1$
traversing the defect core requires $360^\circ$ rotation

$Q = +1/2$

$Q = -1/2$

topological charge $Q = 1/2$
traversing the defect core requires $180^\circ$ rotation

- $+1/2$ and $-1/2$ defects can annihilate to create defect free nematic
- thermal fluctuations are not strong enough to drive spontaneous unbinding of defect pair
- $1/2$ defect only form in a system with nematic symmetry (arrowless bar)
Active liquid crystals exhibit streaming flows!

- equilibrium liquid crystals – static defects
- active liquid crystals – spontaneous motility
aligned extensible filaments are unstable against bend fluctuations
MT active nematics: bucking instability leads to defect creation and annihilation

bend instability leads to buckling

fracture of the director field leads to unbinding of a defect pair

asymmetric $+\frac{1}{2}$ defect is motile

fracture line self-healing
Annihilation of Defect Pairs

Steady state – rate of defect creation is equal to rate of defect annihilation
steady-state rate of defect creation and annihilation
Number of Defects vs Time
Defect Density

Number of Defects per 1mm$^2$

Number of defects / mm$^2$

ATP Concentration (uM)

- plus defects
- minus defects
Tunable Defect Speeds

+1/2 Defects stream faster than -1/2 defects. System is tunable – [ATP] tunes activity

Speeds from inter-frame displacements.
Tunable Defect Speeds

+1/2 Defects stream faster than -1/2 defects.
System is tunable – [ATP] tunes activity

Speeds from inter-frame displacements.
Average Speed vs ATP

![Graph showing the relationship between ATP concentration and average speed. The graph has two lines: one for plus defects and one for minus defects. The x-axis represents ATP concentration in uM, ranging from 0 to 1500, and the y-axis represents speed in um/s, ranging from 0 to 15.]
Defect Lifetimes

The average lifetime of a defect vs ATP concentration.
Defect MSDs

Data for 1.42mM ATP

Asymmetric +1/2 defects drive motion of -1/2 defects.

-1/2 defects exhibit Brownian-like dynamics due to random kicks by +1/2 defects.
Defect MSDs vs ATP
Persistence of Orientation

< θ(t) * θ(t+dt) >

+1/2 Defect Trajectory
Spatial structure of active nematic defects
+1/2 defect from a nematic phase
Time evolution of nematic director
Large Spatial Coherence
Large Spatial Coherence
Defect orientation does not depend on the defect age.
Average Nematic Director Orientation
2D active nematics

- bend deformation is unstable – gives rise to defect generation
- steady state – balanced rate of defect generation and annihilation.
- at larger scales defect organize into a nematic recovering long range order
- defect velocity is determined by activity coefficient (ATP conc)
correlate flow velocity and director dynamics
Motile defects on a spherical surface

Constraint on defect dynamics
- minimize elastic interaction energy
- move with preferred direction
- move with speed determined by activity coefficient (ATP concentration)

What is the defect dynamics on spherical surface?
Are trajectories chaotic or periodic?
Active MT liquid crystals on a 2D circular membrane

- persistent unidirectional circular flows (> 24 hrs)

Total charge = $\frac{1}{2} + \frac{1}{2} + \frac{1}{2} - \frac{1}{2} = +1$

Can two clocks synchronize through hydrodynamic interactions?
What is dynamics of active nematics on an annulus?
Isotropic active gels: solid or liquid?

Daniel Chen

Daniel Blair
Active Isotropic Gels in 3D
MT dynamics in active gels

- extension, polarity sorting and buckling
- bundle fracture
- bundle merging

$6 \, \mu m$
Fluid Flow ATP-dependence: Particle MSD

Totally tunable from subdiffusive to ballistic (equilibrium to non-equilibrium)
Recap, so far...

- assembly of isolated extensile MT bundles
- high bundle concentration – tunable active isotropic gels characterized by spontaneous internal flows, enhanced transport and mixing

Active gels in confined geometries – emergence of spontaneous macroscopic flows
Soft materials that exerts force on their boundaries to produce macroscopic force

How does the observed behavior depend on filament concentration?
Confocal Rheology of Active Networks

Dan Blair (Georgetown University)
Network Morphology $\Leftrightarrow$ Rheology

**Number of Crosslinks**

- 14.2 μM ATP
- no ATP

**Bundle Thickness Distribution**

- no ATP
- 14.2 μM ATP

**Rheology**

- $G'$, $G''$ [Pa]

- 14.2 μM ATP

- frequency (Hz)

- No ATP

- 14.2 μM ATP
Linear Viscoelastic Moduli of Active Network

Network is a gel ($G' > G''$) over entire [ATP] range

$G''/G' \sim 0.3$, damping independent of [ATP]

No relaxation at low frequencies.
Step Strain $\Leftrightarrow$ Anomalous Stress Memory

**Step strain**

\[ \gamma_0 \]
\[ \sigma \]
\[ \tau = \eta/G \]

No ATP, Step strain $\gamma_0 = 100\%$

28.4 μM ATP, Step strain $\gamma_0 = 100\%$

Recoil despite total turnover of network
Active Snake Analysis: Ting Xu, Demetrios Vavylonis, Xiaolei Huang (Lehigh University)
Active Networks perform work

\[ F_N \]

\[ \theta \]

\[ \text{Normal } F_{\text{deg}} (\text{N}) \]

\[ \text{Torque (pN m)} \]

\[ \text{Time (sec)} \]

\[ \text{Time (sec)} \]