# *ABSTRACTS*

## ***Nonlinear dynamics of multilayer flows in channels***

Demetrios Papageorgiou

We consider the stability of multilayer flows in channels driven by gravity and pressure gradients. We concentrate on the case of three immiscible viscous fluids so that two interfaces separate the three regions. Using long wave asymptotic methods we first derive a coupled Benney-type system of equations to describe the dynamics. It is shown that an asymptotically correct weakly nonlinear model can be found if the flow parameters (undisturbed interfacial position, density and viscosity ratios) are chosen to be an umbilic hyperbolic point of the leading order advection matrix. A detuning of these parameters then leads to canonical systems of coupled Kuramoto-Sivashinsky like PDEs. These can have flux functions that are strictly hyperbolic or that can be of mixed hyperbolic-elliptic type. Surface tension provides a fourth order regularization for each equation and acts to damp short waves that can emerge from ellipticity or other instabilities. Of particular interest is the kinematic instability that emerges from the asymptotic detuning and which can interact with the viscous terms to provide long wave instability (a type of Majda-Pego instability for a high order system). Numerical solutions using spectral methods and implicit solvers to account for the stiffness, predict that in the absence of inertia the non-trivial large-time solutions that emerge are nonlinear traveling waves, whereas when inertia is present the solutions exhibit spatiotemporal chaos. This can be controlled by the kinematic term, however, if the latter is sufficiently large.

## ***Liquid/liquid dewetting - theory and experiments***

Dirk Peschka, Weierstrass Institute, Berlin.

In this talk we compare morphologies of liquid lenses observed in liquid/liquid dewetting experiments to solutions of corresponding thin-film equations. Particular emphasis will be given to the treatment of the liquid/liquid/air triple-junction either as a sharp line or using a precursor film on the liquid substrate. The equivalence of both approaches can be shown rigorously for energetic minimisers using Gamma-convergence. Beyond equilibrium states we use numerical solutions of time-dependent problems to show that both approaches agree very well with respect to the observed morphologies as well as to the observed the time-scale. With this independence in mind we use a thin-film model with precursor to compare numerical solutions and experiments of liquid lenses near their equilibrium and find nice agreement even beyond region where lubrication theory is expected to hold.

## ***Nanofluidics of thin films: Linking stability and dynamics of liquid layers to microscopic material properties***

Karin Jacobs, Oliver Baeumchen, Matthias Lessel, Mischa Klos and Sabrina Haefner
Experimental Physics, Saarland University, D-66041 Saarbrücken, Germany

Whether a lubricant or a coating wets a surface or not is of great technical importance. Theoretically, it is possible to predict the stability of a thin liquid film on a surface, since it is governed by the effective interface potential. In practice, however, a prediction can be quite cumbersome, since liquids as well as surfaces often consist of numerous components which all influence the effective interface potential, some of which will be discussed in the talk. If the film is not stable, distinct rupture mechanisms can be observed, causing characteristic film morphologies: spinodal dewetting and dewetting by nucleation of holes, which both entail liquid flow and reveal new routes to study microscopic parameters such as the hydrodynamic boundary condition at the solid/liquid interface. Rather old questions turn out to become very important again: Can liquids slide? Or: Is the glass transition temperature a function of the substrate material? The talk links stability and dynamics of thin liquid films to microscopic material properties (effective interface potential, viscosity, slip length...), which may serve e.g. as input parameters into simulations and, moreover, describes their experimental access.

## *Fluid Rings*

Brian R. Duffy, Department of Mathematics and Statistics, University of Strathclyde

*Joint work with Adam Leslie and Stephen K. Wilson (University of Strathclyde)*

In this talk the steady three-dimensional flow of a thin, slowly varying ring of Newtonian fluid on either the outside or the inside of a uniformly rotating large horizontal cylinder will be described. Specifically, we study ``full-ring'' solutions, corresponding to a ring of continuous, finite and non-zero thickness that extends all the way around the cylinder. In particular, it is found that there is a critical solution corresponding to either a critical load above which no full-ring solution exists (if the rotation speed is prescribed) or a critical rotation speed below which no full-ring solution exists (if the load is prescribed).

We describe the behaviour of the critical solution and, in particular, show that the critical flux, the critical load, the critical semi-width and the critical ring profile are all increasing functions of the rotation speed. In the limit of small rotation speed, the critical flux is small and the critical ring is narrow and thin, leading to a small critical load. In the limit of large rotation speed, the critical flux is large and the critical ring is wide on the upper half of the cylinder and thick on the lower half of the cylinder, leading to a large critical load.

We also describe the behaviour of the non-critical full-ring solution, and, in particular, show that the semi-width and the ring profile are increasing functions of the load but, in general, non-monotonic functions of the rotation speed. In the limit of large rotation speed, the ring approaches a limiting non-uniform shape, whereas in the limit of small load, the ring is narrow and thin with a uniform parabolic profile.

Finally, we show that, while for most values of the rotation speed and the load the azimuthal velocity is in the same direction as the rotation of the cylinder, there is a region of parameter space close to the critical solution for sufficiently small rotation speed in which backflow occurs in a small region on the upward-moving side of the cylinder.

Full details are given in the forthcoming paper: G.A. Leslie, S.K. Wilson and B.R. Duffy, Three-dimensional coating and rimming flow: a ring of fluid on a rotating horizontal cylinder, J. Fluid Mech. (2012), to appear.

## *Liquid morphologies and their manipulation on liquids and elastic grooved substrates*

Ralf Seemann[1,2], Konstantina Kostourou[2], Stefan Bommer[1], Carsten Herrmann[1], Dominik Michler[1,2], Stephan Herminghaus[2], Martin Brinkmann[1,2], Dirk Peschka[3] , Barbara Wagner[3],

[1] Experimental Physics, Saarland University, 66123 Saarbrücken, Germany
[2] MPI for Dynamics and Self-Organization, 37073 Göttingen, Germany
[3] Weierstrass Institute for Applied Analysis and Stochastics, Berlin, Germany

In linear solid grooves various wetting morphologies can be found which depend on geometry and wettability of the grooves. The most basic wetting morphologies are droplet shapes sitting on top of the grooves and elongated filament morphologies confined to the grooves with finite length having either positive or negative mean curvature. Varying the apparent contact angle by electrowetting we can switch between liquid morphologies and thus transport liquid along grooves. Depending on the particular groove geometry the transport of liquid is reversible or irreversible. The emerging instability can be understood as Rayleigh Plateau instability and even allows to study slip properties at the solid/liquid interface.

The appearance of wetting morphologies is altered if the grooves are made from a rubber elastic material (poly-dimethylsiloxane (PDMS)). The geometry of such grooves can locally vary upon the appearance of liquid morphologies resulting in an even larger number of stable liquid morphologies. The deformation of grooves is the more pronounced the softer the substrates and might even result in a lateral ordering of the wetting morphologies if the substrate contains several parallel grooves separated by thin elastic ridges. By stretching and relaxing the elastic groove geometries one can switch between different liquid morphologies. Surprisingly, the thus induced flow of liquid along rubber elastic grooves is much slower than the flow in solid grooves. The resulting deformation of the liquid/substrate interface is studied quantitatively using a simpler to handle liquid/liquid polymer system.

## *Existence and long-time behavior of weak solutions for the Mullins equation*

Marina Chugunova, Roman Taranets
(Claremont Graduate University, University of Nottingham)

We study the initial–boundary value problem for the fourth order Mullins equation under an assumption that the specific free energy of the boundary is less than the surface free energy. The model was derived by Mullins in 1957 to analyze the time-evolution of surface grooves at the grain boundaries of a heated polycrystal. We prove global in time existence of weak solutions and we also show that the energy minimizing steady state is the global attractor.

## *Influence of surfactant concentration and roughness on the dynamics close to advancing and receding contact lines*

*Günter K. Auernhammer*
*Max Planck Institute for Polymer Research, Mainz, Germany*

We investigate dynamic wetting of surfactant solutions in a rotating drum setup and thin capillaries. The presence of minor amounts of surfactants (typically well below the critical micelle concentration) in the wetting liquid induces pronounced modifications especially in the dewetting behavior. In a few examples, dynamic contact angles and flow profiles will be discussed.

Forced wetting and dewetting of polymer surfaces in aqueous solutions containing cationic surfactant cetyltrimethylammonium bromide (CTAB) has been studied with a rotating cylinder half immersed in the solution. The receding contact angle decreases with faster withdrawing speeds [1]. This decrease is enhanced when adding CTAB. The addition of salt to the CTAB solution further enhances the effect but does not have a significant effect alone.

The influence of local and nonlocal transport processes of CTAB molecules on dynamic contact angles and contact angle hysteresis was also studied in the rotating drum setup. The influence of long-range surfactant transport was analyzed by hindering selectively the surface or the bulk transport via movable barriers. With increasing hindrance of the surfactant transport, the receding contact angle decreased at all withdrawing velocities in the presence of CTAB [2]. The control experiment with pure water was unaffected by the presence of the barriers. Dynamic contact angles are, therefore, not only influenced by short-range effects like Marangoni stresses close to the contact line, but also by long-range transport processes (like diffusion and advection) between the regions close to the receding and advancing contact lines.

We report on the time-dependent dewetting behavior of dilute surfactant solutions of CTAB during forced flow in fluorinated ethylenepropylene (FEP) microtubes. The dynamic receding contact angle of the solution at a given velocity decreased as the solid-liquid contact time increased [3]. Kinetics with long relaxation time of several hundred seconds led to a final state displaying a 0° dynamic receding contact angle. This effect was absent in the case of 2-propanol, where the dynamic receding contact angle did not depend on the contact time.

**References:**

1. Daniela Fell, Günter K. Auernhammer, Elmar Bonaccurso, Chuanjun Liu, Mordechai Sokuler, and Hans-Jürgen Butt, *Influence of Surfactant Concentration and Background Salt on Forced Dynamic Wetting and Dewetting,* Langmuir **27**, 2112-2117 (2011).
2. Daniela Fell, Ngamjarassrivichai Pawanrat, Elmar Bonaccurso, Hans-Jürgen Butt, and Günter K. Auernhammer, *Influence of surfactant transport suppression on dynamic contact angle hysteresis*, Colloid Polymer Sci., DOI: 10.1007/s00396-012-2759-y (2012).
3. Manos Anyfantakis, Daniela Fell, H.- J. Butt, G. K. Auernhammer, *Time-dependent Dynamic Receding Contact Angles Studied during the Flow of Dilute Aqueous Surfactant Solutions through Fluorinated Microtubes*, Chem. Lett. **41**, 1232-1234 (2012).

## *Slip or not slip? A comparison of models applied to contact line motion*

David Sibley, Andreas Nold, Nikos Savva and Serafim Kalliadasis
Department of Chemical Engineering, Imperial College London

The motion of a contact line is examined, and comparisons drawn, for a variety of proposed models in the literature. We first analyse a contemporary model based on interface formation introduced by Shikhmurzaev, which differentiates itself from classical models through accounting for a variation in surface layer quantities and having finite-time surface tension relaxation. This model is scrutinised in the classic test-bed system of spreading of a thin two-dimensional droplet on a planar substrate, a prototype of central importance to the workshop. The implementation of a long-wave model for the droplet thickness in a quasistatic spreading regime affords an insight into the interface formation model behaviour, principally that the evolution of the droplet radius reduces to an equivalent expression for a slip model when the prescribed dynamic contact angle has a velocity dependent correction to its static value. Analysis of a solid-liquid-gas diffuse-interface model is then presented, showing the resolution of the stress and pressure singularities associated with the moving contact line problem in this case, with comparisons then drawn to the previous models discussed.

## *On the source of temperature pulsations during sessile droplet evaporation*

Aaron H. Persad, Charles A. Ward
Thermodynamics and Kinetics Laboratory, Department of Mechanical and Industrial Engineering, University of Toronto
and Khellil Sefiane
The Institute for Materials and Processes, School of Engineering, The University of Edinburgh

In a wide range of fields, temperature is the basic parameter used to characterize processes, but the reliability of temperature measurements is brought into question by recent observations. Reported infrared thermography data of ethanol evaporating into room air indicated spontaneous temperature pulsations of up to 1.5 . [1], but reported thermocouple measurements of ethanol evaporating into its own vapour did not indicate any temperature pulsations [2]. These pulsations have been suggested to result from the excitation of hydrothermal waves during evaporation [3, 5]. We have constructed an apparatus in which sessile droplets of di_erent liquids evaporate steadily or unsteadily from a polytetrauoroethylene (PTFE) substrate into atmospheres of controlled humidity. For both ethanol and methanol, we find that the temperature pulsations measured with thermocouples agree with the IR thermography results reported elsewhere [1, 3, 5, 6]. Furthermore, we show that the temperature pulsations occur only if the relative humidity is above a threshold value. No temperature pulsations are observed when water evaporates into room air. However, when water evaporates into a methanol-water vapour mixture, temperature pulsations are present. Pressure measurements in the atmosphere of evaporating droplets indicate that the source of the temperature pulsations is pulsations in the evaporation

[1] D. Brutin, B. Sobac, F. Rigollet, and C. L. Niliot, Experimental Thermal and Fluid Science 35, 521 (2011).
[2] A. H. Persad and C. A. Ward, J. Phys. Chem. B 114, 6107 (2010).
[3] K. Sefiane, A. Steinchen, and R. Mo_at, Colloids and Surfaces A: Physicochem. Eng. Aspects , 95 (2010).
[4] A. Wierschem, H. Linde, and M. G. Velarde, Phys. Rev. E. 62, 6522 (2000).
[5] B. Sobac and D. Brutin, Physics of uids 24, 032103 (2012).
[6] K. Sefiane, J. R. Moffat, O. K. Matar, and R. V. Craster, Appl. Phys. Lett. 93, 074103 (2008).

### *Wetting dynamics on chemically heterogeneous substrates*

Daniel Herde, Max Planck Institute, Germany

Wetting dynamics play an important role in processes ranging from photolithography to enhanced oil recovery. Even though relevant in most applications, the dynamic wetting and dewetting on chemically or topographically patterned substrates is not yet completely understood. Since this problem requires modeling the system over some length scales, we used boundary element methods to numerically study advancing and receding contact lines on substrates with a position dependent wetting energy for high contact angles. The goal is to understand the effect of the strength and periodicity of the heterogeneity on the dynamic contact angle observed for a contact line driven with a constant velocity. We show that the time-averaged microscopic contact angle together with the contribution of the bulk dissipation observed on a homogeneous substrate is a good predictor for the time-averaged macroscopic contact angle observed on a heterogeneous substrate.

### *Films, rings, and rivulets: Instabilities of liquid metals on nanoscale*

Lou Kondic, New Jersey Institute of Technology

We will start by discussing techniques used to model thin films and rivulets within the framework of long-wave theory. The emphasis will be on the interactions of various types of instabilities in the geometries involving fluid fronts and contact lines. In the second part of the talk, we apply our results to breakup of nano-scale metal films, rivulets and rings liquefied by repeated laser pulses. An additional aspect of the problem is the fact that the details of metal/substrate interaction are not well known, and we will discuss our attempts towards solving an inverse problem of deducing this interaction from the experimentally observed breakup of metal films. Then, we will consider the instability development of patterned rivulets and rings, and discuss how well the long-wave theory captures the experimental results. We will conclude by discussing preliminary results in the two directions (i) directed assembly of metal geometries on nanoscale, and (ii) modeling based on full Navier-Stokes formulation.

### *Capillary fracture of soft gels*

J.B. Bostwick, M. Schillaci and K.E.Daniels

A droplet of surfactant spreading on a gel substrate can produce fractures on the gel surface, which originate at the contact-line and propagate outwards in a star-burst pattern. Experiments show that the number of arms is controlled by the ratio of surface tension contrast to the gel's shear modulus. To further understand the mechanism behind crack initiation, we model the gel as a linear elastic solid and compute the state of stress that develops within the substrate from the uncompensated contact-line forces. The elastic solution yields an effective metric to predict the number of fractures and, hence, an interpretation of the initiation process. We also show that the depth of the gel is critical parameter in the fracture process, as it can help mitigate large surface tractions. This observation is confirmed in preliminary experiments. After the onset of fracture, experiments show the arm length grows with universal power law $L=t^{3/4}$ that does not scale with any material parameters (Daniels et al. 2007, PRL). We develop a model for crack growth by considering the transport of an inviscid fluid into the fracture tip of a Neo-Hookean (incompressible) material. Our model predicts the aforementioned experimental results and also explains why such results also hold for super-spreading surfactants (Spandangos et al. 2012, Langmuir).

## *Fast Evaporation of Spreading Droplets of Colloidal Suspensions*

K.L. Maki and S. Kumar

When a coffee droplet dries on a countertop, a dark ring of coffee solute is left behind, a phenomenon often referred to as ``the coffee-ring effect.'' A closely related yet less-well-explored phenomenon is the formation of a layer of particles, or skin, at the surface of the droplet. In this work, we explore the behavior of a mathematical model that can qualitatively describe both phenomena. We consider a thin axisymmetric droplet of a colloidal suspension on a horizontal substrate undergoing spreading and rapid evaporation. The lubrication approximation is applied to simplify the mass and momentum conservation equations, and the colloidal particles are allowed to influence droplet rheology through their effect on the viscosity. By describing the transport of the colloidal particles with the full convection-diffusion equation, we are able to capture depthwise gradients in particle concentration and thus describe skin formation, a feature neglected in prior models of droplet evaporation. Whereas capillarity creates a flow that drives particles to the contact line to produce a coffee-ring, Marangoni flows can compete with this and promote skin formation. Increases in viscosity due to particle concentration slow down droplet dynamics, and can lead to a significant reduction in the spreading rate.

## *Thin film evolution equations for complex fluids - extensions based on a gradient dynamics formulation*

Uwe Thiele, Loughborough University

After reviewing a number of recent experiments [1] on evaporating and dewetting thin films of suspensions and solutions, we propose a way to construct dynamical models for liquid films of suspensions and solutions, as well as for films covered by insoluble surfactants. First, we briefly review the `classical' hydrodynamic form of the coupled evolution equations for the film height and (solute or surfactant) concentration that are well established for small concentrations; and mention recent results on line deposition from evaporating suspensions [2].

Then we re-formulate both basic hydrodynamic models as a gradient dynamics based on an underlying free energy functional that accounts for wettability and capillarity of the solvent. Based on this mere re-formulation in the framework of nonequilibrium thermodynamics, we propose extensions of the basic hydrodynamic models that may account for (i) surfactant- or solute-dependent wettability, and (ii) surfactant or solute phase transitions [3,4]. Other possibilities are mentioned and examples are sketched for (i) and (ii).

[1] for a small review see: U. Thiele et al., J. Phys.-Cond. Mat. 21, 264016 (2009).
[2] L. Frastia, A. J. Archer, U. Thiele, Phys. Rev. Lett. 106, 077801 (2011); Soft Matter 8, 11363-11386 (2012).
[3] U. Thiele, Eur. Phys. J. Special Topics, 197, 213-220 (2011).
[4] U. Thiele, A. J. Archer and M. Plapp, Phys. Fluids 24, 102107 (2012).

### *Quasi-Immiscible Spreading of Aqueous Surfactant Solutions on Aqueous Entangled Polymer Solutions*

R. Sharma, A. Khanal, E. Swanson, T. Corcoran, S. Garoff, T. Przybycien, R. Tilton

Motivated by the potential for surface tension gradient driven flows to move exogenous drug-containing fluids through the lungs, this presentation concerns the spreading of aqueous surfactant solutions over entangled aqueous polymer solutions, including mucin and simpler polyacrylamide solutions, that mimic the physical properties of airway surface liquid. Surfactant solutions contain dyes that not only serve as tracers but also as drug mimics, modeling the use of surfactant formulations as self-dispersing pulmonary drug delivery vehicles. Anionic, cationic and nonionic surfactants are compared in order to determine the potential impact of surfactant-macromolecule binding on the extent of spreading. For all surfactants and subphases examined, Marangoni stresses initiate flow, and convective spreading terminates with the spread solution confined to a well-defined static area. Spreading times are on the order of tens of seconds, considerably shorter than the timescales for diffusion into the subphase bulk or for subphase disentanglement. Spreading occurs as if the aqueous surfactant solution and aqueous subphase were immiscible. The spread drop forms a static lens that exists for ~10 minutes and must satisfy the capillary force balance while its contents slowly diffuse into the subphase. Similar behaviors occur on both polyacrylamide and mucin solutions, for all three types of surfactants, despite the significant difference in chemistry and association properties of these systems. The independence of spreading behaviors on the chemistry of the surfactant and subphase indicates that the spreading process and final solution distributions are controlled by general capillary and hydrodynamic phenomena and not specific interactions among system components.
We acknowledge the support of NIH grant 1 R01 HL105470-01A1 and NSF grants CBET-0931057 and DMS-0635983.

### *Floating Plates*

Stephen K. Wilson, Department of Mathematics and Statistics, University of Strathclyde.
Joint work with Phil Trinh (University of Oxford) and Howard Stone (Princeton).

In this talk I will discuss a rigid plate moving steadily on the free surface of a thin film of fluid. As well as having been proposed as model for the motion of a contact lens in the eye, this paradigm problem is relevant to a wide range of fluid-structure interaction problems involving a free surface (such as, for example, flexible blade coating).

Specifically, I shall study two problems involving a rigid flat (but not, in general, horizontal) plate: the pinned problem, in which the upstream end of plate is pinned at a fixed position, the fluid pressure at the upstream end of the plate takes a prescribed value and there is a free surface downstream of the plate, and the free problem, in which the plate is freely floating and there are free surfaces both upstream and downstream of the plate. For both problems, the motion of the fluid and the position of the plate (and, in particular, its angle of tilt to the horizontal) depend in a non-trivial manner on the competing effects of the relative motion of the plate and the substrate, the surface tension of the free surface, and of the viscosity of the fluid, together with the value of the prescribed pressure in the pinned case. Specifically, for the pinned problem I shall show that, depending on the value of an appropriately defined capillary number and on the value of the prescribed fluid pressure, there can be either none, one, two or three equilibrium solutions with non-zero tilt angle. Furthermore, for the free problem I shall show that the solutions with a horizontal plate (i.e. zero tilt angle) conjectured by Moriarty and Terrill (1996) do not, in general, exist, and in fact there is a unique equilibrium solution with, in general, a non-zero tilt angle for all values of the capillary number. Finally, if time permits some preliminary results for an elastic plate will be presented.

This work was begun while I was a Visiting Fellow in the Department of Mechanical and Aerospace Engineering, School of Engineering and Applied Science, Princeton University, USA, and part of it was undertaken while I was a Visiting Fellow in the Oxford Centre for Collaborative Applied Mathematics (OCCAM), Mathematical Institute, University of Oxford, United Kingdom, the latter supported in part by Award No KUK-C1-013-04 made by King Abdullah University of Science and Technology (KAUST).

J.A. Moriarty and E.L. Terrill, Mathematical modelling of the motion of hard contact lenses, Euro. J. Appl. Math. 7, 575--594 (1996).

### *Settling Dynamics of a Contact Lens*

K.L. Maki, D.S. Ross, and E. Holz

We study the settling dynamics of the contact lens to better understand how the design of the lens can be optimized for patient comfort and ocular fit. When a contact lens is inserted on an eye, it is subjected to forces from both the tear film in which it is immersed as well as those of an blink, and in response, the lens bends and stretches. These forces allow for proper lens centration, and create the suction pressure responsible for keeping the lens on the corneal surface. In this talk, we couple fluid and solid mechanics to determine the most prominent forces acting on the lens. A mathematical model is presented that predicts the changes in pressure distribution and lens shape over time. We explore the role of contact lens properties in influencing centering and lens fit. This work is in collaboration with Bausch + Lomb.

### *Clear-fluid and particle-laden flows in helical channels*

Yvonne Stokes, University of Adelaide

The study of flow in open helically-wound channels has application to many natural and industrial flows. We will consider laminar flow down helically-wound channels of rectangular cross section and with small torsion, in which the fluid depth is small. Assuming a steady-state flow that is independent of position along the axis of the channel, the flow solution may be determined in the two-dimensional cross section of the channel. A thin-film approximation further simplifies the model.

In the case of a clear fluid, having constant density and viscosity, the thin-film model yields explicit expressions for the fluid velocity in terms of the free-surface shape. The latter satisfies an interesting non-linear ordinary differential equation that, for a channel of rectangular cross section, has an analytical solution. The thin-film model shows excellent agreement with much more computationally intensive solutions of the small-helix-torsion Navier–Stokes equations. Early work on adapting the clear fluid model to a particle-laden flow, having density and viscosity that depend on the volume fraction of particles, will also be discussed. This makes use of recent work on flow of slurries down inclined planes.

This work has particular relevance to spiral particle separators used in the minerals processing industry.

### *Viscous currents spreading under an elastic lid*

John Lister
Institute of Theoretical Geophysics, DAMTP, University of Cambridge

In lubrication theory, viscous gravity currents are controlled by the interior dynamics and the contact line is not a problem. By contrast, capillary-driven flows require a slip model or prewetting film to resolve the contact-line problem, though the influence of this model is weak. In this talk, I show that the contact-line problem for flow beneath an elastically deformable boundary is yet more acute and requires matched asymptotic solutions over a hierarchy of nested length and time scales.

This point is illustrated theoretically and experimentally by the injection and spread of viscous fluid beneath a flexible elastic lid with a prewetting film. The experimental measurements of surface elevation and radial propagation are in good agreement with lubrication calculations incorporating bending stresses and gravity. Remarkably, even this simple system evolves through four asymptotic regimes with successive radial spreading laws $r \sim t^{1/6}, t^{7/22}, t^{7/12}$ and $t^{1/2}$. Alternate problems without the prewetting film yield yet more exotic scalings. The analysis of wet and dry elastic peeling processes in these relatively simple problems gives insight for applications to more complex multiscale interfacial deformation problems such as cell adhesion, delamination, and the dynamics of MEMS.

### *Chemical reaction-driven tip-streaming: the true nature*

R. Krechetnikov (joint work with H.C. Mayer)
University of California, Santa Barbara

This is a story of the discovery made about a decade ago during measurements of the dynamic interfacial tension of a water-alkali pendant drop immersed in the oil-linoleic acid mixture. The plausible explanation for the self-sustained ejection of micron sized droplets from the tip of the 0.5 mm pendant drop on the capillary was offered at that time and attributed to Marangoni stresses driving surfactant along the drop interface. As this chemical reaction-driven tip-streaming promised the way of microdroplet generation without the need for complex microchannel geometries or externally imposed flow or electric fields, we were motivated to study the influence of the chemical concentrations on the tip-streaming. However, in attempt to recreate the original experiments, we ended up revealing that it is not what it originally seemed, which also led to a series of experiments clarifying the role of the chemical reaction and Marangoni stresses as well as crucial differences from the known similar phenomena. The present study brings a new intrigue: as the Marangoni-driven mechanism, by which the chemical reaction-driven tip-streaming was originally thought to operate, was supported by recent theoretical studies, our new experimental findings lead to the question on the conditions under which the chemical reaction alone can drive Marangoni stresses capable of self-sustaining the tip-streaming.

### *Dynamic Wetting Failure and Air Entrainment: What can Thin-Film Models Teach Us?*

Satish Kumar, Chemical Engineering and Materials Science (CEMS), University of Minnesota

Dynamic wetting is crucial to processes where liquid displaces another fluid along a solid surface, such as the deposition of a coating liquid onto a moving substrate. Numerous studies report the occurrence of dynamic wetting failure and air entrainment past some critical process speed. However, the factors that influence this transition remain poorly understood from an empirical and theoretical perspective. In this talk, I will discuss the results from experiments and hydrodynamic modeling aimed at addressing this issue. The experiments involve two novel devices that allow for systematic determination of the influence of meniscus confinement. The hydrodynamic model is analyzed with (i) lubrication theory and (ii) a two-dimensional finite-element method (FEM). Wetting failure is found to coincide with turning points in steady-state solution paths. While both approaches (i) and (ii) do a remarkable job of qualitatively matching experimental observations, only the two-dimensional model yields quantitatively accurate predictions due to the highly two-dimensional nature of the stress field in the displacing liquid. The implications of these observations for the utility of thin-film modeling and the physical mechanisms of air entrainment will be discussed.

### *Self-similar rupture of thin heated viscous sheets*

B.S. Tilley, WPI, and M. Bowen, Waseda University

We consider the evolution and rupture dynamics of a thin viscous planar sheet subject to a symmetric initial disturbances in the thermal and velocity fields. We consider the long-wave limit where deviations from the mean sheet velocity are small, but thermocapillary stresses, fluid inertia, van der Waals effects, capillarity, and heat transfer to the environment can be significant. The result is a coupled system of three equations that describe the sheet thickness, the sheet velocity, and the sheet temperature. When van der Waals effects are dominant, the sheet ruptures due to disjoining pressures for sufficiently long-wave disturbances on a faster time-scale than convection or conduction. However, in cases when disjoining pressures are small, we find a self-similar rupture process where inertia, viscous stresses, thermocapillarity, convection and conduction all balance. We quantify how solutions can transition from this similarity solution to the van-der-Waals-driven self-similar solution when the thickness of the sheet becomes sufficiently thin.

### *Rising of Immiscible Droplets in Density Stratified Fluids*

Shilpa Khatri, University of North Carolina

The fluid dynamics of droplets rising and particles settling in density stratified fluids is vital to understanding the effect of stratification in marine settings. Whether studying particles settling or droplets rising, similar small scale dynamics are observed. An example of rising is provided by immiscible oil droplets rising, which occur in the environment as oil seeps and jets in the ocean. As a first step towards understanding these dynamics, we study the case of an oil droplet rising in water stratified by salt. Preliminary results of experiments will be presented for both low and moderate Reynolds numbers. Also, a discussion of the modeling underway for this system will be included. Similarities and differences with the case of settling particles will also be presented.

***Biaxial Extensional Motion of an Inertially Driven Circular Sheet***

Linda Smolka, Bucknell University

We consider the inertially driven, time-dependent biaxial extensional motion of inviscid and viscous thinning liquid sheets. We present an analytic solution describing the base flow and examine its linear stability to varicose (symmetric) perturbations within the framework of a long-wave model where transient growth and long-time asymptotic stability are considered. The stability of the system is characterized precisely in terms of the perturbation wavenumber, Weber number and Reynolds number. We find the isotropic nature of the base flow yields linearized stability results that are identical for axisymmetric and general two-dimensional perturbations. Transient growth of short-wave perturbations can have significant and lasting influence on the long-time sheet thickness. For any finite Reynolds number a radially-expanding sheet is asymptotically marginally unstable, whereas in the inviscid and Stokes flow limits the sheet is unstable.

## *Autophobing on Liquid Subphases via Interfacial Transport of Amphiphilic Molecules*

R. Sharma, E. Swanson, T. Corcoran, S. Garoff, T. Przybycien, R.Tilton

Autophobing is a phenomenon in which a low surface tension drop of pure amphiphilic molecules or a solution of amphiphiles fails to completely wet a high energy substrate and instead forms a lens. Considerable research has examined autophobing on solid substrates, where questions still remain about the balance of surface tensions in the final state and what molecular structures produce those surface tensions. Autophobing has also been observed on liquid subphases. Autophobing on liquids has been attributed to molecular transport through one of the bulk phases rather than to interfacial transport. Motivated by Marangoni driven spreading on liquid subphases, we investigate the mechanism of autophobing on liquid subphases via interfacial transport of amphiphiles. We deposit drops of a pure amphiphilic compound (oleic acid) or of a surfactant solution (dodecanol in hexadecane) on water or glycerol-water mixture subphases. The low solubility and vapor pressure of the deposited amphiphiles make it highly unlikely that bulk phase transport of the molecules can cause the drop to autophobe on the short timescales observed here. We measure surface tensions relevant to the spreading both before and after drop deposition, determine if the amphiphiles have moved from the drop onto the surrounding subphase surface outside the lens, and estimate the packing of those molecules on the surface. In all cases, we observe the rapid escape of amphiphiles across the drop contact line promptly after drop deposition and formation of a monolayer that is close to collapse on the subphase outside the drop. The monolayer formation decreases the subphase-air surface tension external to the drop and reverses the sign of the spreading coefficient from positive (before the monolayer forms) to negative, forcing the drop to retract into a lens with an increased contact angle. Measurement of all three surface tensions that exist at the end of drop spreading reveals that it is the reduction in the surface tension of the subphase outside the drop that is solely responsible for inhibiting the spreading of the drop and initiating its retraction. Further, we capture the dynamic retraction of an oleic acid drop on a glycerol-water mixture subphase by simultaneously tracking the movement of the drop contact line and the capillary ridge that advances ahead of the drop contact line. We clearly see that the drop does not spread completely to a thin wetting film with zero degree contact angle despite the initially positive spreading coefficient. Rather it first spreads only to a finite extent and then starts retracting once the amphiphilic molecules have oriented themselves to form a dense monolayer outside the drop. In addition, we also develop a mathematical model to predict the diameter of the lens given all the surface tensions, densities and the deposited drop volume. We compare the experimentally measured lens diameters with the mathematical model and find the values to be in good agreement.

### *Bifurcation, thin film structure and collapse in Newton's bucket.*

Joshua A. Dijksman, Shomeek Mukhopadhyay, Tom Witelski, Richard Mclaughlin, Roberto Camassa and Robert P. Behringer

The understanding of rotating thin film flows is of great fundamental and practical (spin coating, geophysical flows) importance. In this talk we will present our ongoing work with the second generation of a spin coating apparatus with walls that we call "Newton's bucket". We study the bifurcation of the dry spot that develops above a critical rotation rate. We observe a nontrivial fine structure in the contact line that connects the dry spot with the fluid reservoir and measure the collapse dynamics of the fluid reservoir by means of high speed imaging. We compare our observations to numerical solutions of the lubrication approximation. Supported by NSF-DMS-09-68252.

### *Models for Tear Film Dynamics*

Rich Braun, University of Delaware

The flow over a two dimensional eye-shaped domain with time dependent boundary conditions will be discussed. The fresh tear fluid supplied is typically unable to flow into the middle area of the eye without blinking, particularly with evaporation. The deformation of the meniscus in vivo and in silico closely resemble each other. Then, local dynamics for the tear film emphasizing the role of the lipid layer and osmolarity (saltiness) will be presented. A mechanism for tear film breakup (film rupture) involving evaporation and excess polar lipid (insoluble surfactant) gives a prediction for the increased osmolarity in the breakup regions; no experimental results are available that measure this quantity though it is thoughtto be critical to the development of symptoms in dry eye.

### *Microfluidic processing of complex fluids*

Joao P. Cabral

### *Linear structures of nanodrops generated from patterned filaments*

L. Kondic, A. Gonzalez, J. Diez, J. Fowlkes, Y. Wu, C. Roberts, C. McCold, P. Rack

Liquid metal filaments supported on substrates, destabilize into droplets. The destabilization mechanism exhibits many characteristics of the Rayleigh–Plateau instability mechanism for a fluid jet destabilization. In either case, liquid breakup is driven by a multitude of unstable, varicose surface oscillations with a wavelength greater than the critical one. Here, by controlling the nanosecond liquid lifetime of the metal filaments and their initial shape, we demonstrate experimentally the ability to dictate the formation of connected wires and droplets simultaneously with precise placement. The results are interpreted within the context of the long-wave theory. More details can be found in Nanoscale, Vol. 4, 7376 (2012). Supported in part by NSF CBET-1235710.

## *Nanometric rings: Molecular dynamics and continuum modeling*

L. Kondic, J. Diez, A. Gonzalez, T. Nguyen, M. Fuentes-Cabrera, J. Fowlkes, P. Rack

We consider nanometer-sized fluid annuli (rings) deposited on a solid substrate and ask whether these rings break up into droplets due to the instability of Rayleigh-Plateau type modified by the presence of the substrate, or collapse to a central drop due to the presence of azimuthal curvature. The analysis is carried out by a combination of atomistic molecular dynamics simulations and of a continuum model based on a long-wave limit of Navier–Stokes equations. We find consistent results between the two approaches, and demonstrate characteristic dimension regimes which dictate the assembly dynamics.
More details can be found in Langmuir, Vol. 28, 13960 (2012).
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## *Acoustowetting: Film Spreading, Fingering Instabilities and Soliton-Like Wave Propagation*

Ofer Manor, Amgad Rezk, James R. Friend and Leslie Y. Yeo
*Micro/Nanophysics Research Laboratory, RMIT University, Melbourne, Victoria 3000, Australia*

Radio frequency (1–100 MHz) solid vibration modes, such as Rayleigh surface acoustic-waves (SAWs), are generated by piezoelectric actuators that transfer electric signal to kinetic energy and give rise to different types of flow regimes when in contact with a viscous fluid, known in general as acoustic streaming. One of which, a viscous flow that appears near the vibrating solid and is related to the Schlichting boundary layer, is found to provoke the constant spreading of thin liquid films and various instabilities.

Thin viscous films having a natural 10–60 micron thickness, governed by acoustic resonance, spread in opposition to the SAW propagation. The spreading films undergo an instability triggered by SAW diffraction to form fingering patterns above which soliton-like wave pulses are observed to grow and translate in the opposing direction. The intensity of the fingering patterns is related to the level of diffraction and may be reduced by slightly off resonance excitations. In addition to deriving a dynamic spreading model we show the competing influence of different mechanisms, invoked in the process of energy transfer from SAWs to fluid flow, that render flow reversal at different length scales manifested in the opposite wetting directions undertaken concurrently by thin films and drops.