On instabilities of Finite-size Films and Rivulets

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Abstract: We discuss the influence of finite size effects on the breakup process involving finite-size films and rivulets. For films, we show that the breakup process due to finite size effects can be related to the so-called nucleation mode of instability of infinite films. We also consider coupling of different modes of instabilities, and the competition between them. Next, we revisit the classical problem of rivulet instability and discuss whether finite size effects may be important in determining relevant breakup mechanisms. We apply our results to rupture of nano-scale metal lines irradiated by repeated laser pulses and discuss relevance of the considered process to self-assembly

Formulation

Thin film approach with gravity and finite contact angle modeled using disjoining pressure approach with disjoining and conjoining components:

$$\frac{\partial h}{\partial t} + \nabla\cdot\left(h^3\nabla\nabla^2 h\right) + K\nabla\cdot\left[h^3 f'\nabla h\right] - D\nabla\cdot\left(h^3\nabla h\right) = 0$$

$$\Pi(h) = \kappa f(h) = \kappa\left[\left(\frac{h_*}{h}\right)^n - \left(\frac{h_*}{h}\right)^m\right]$$

$$\kappa = \frac{S}{M h_*}; M = \frac{(n-m)}{(m-1)(n-1)}; S = \gamma(1-\cos\theta)$$

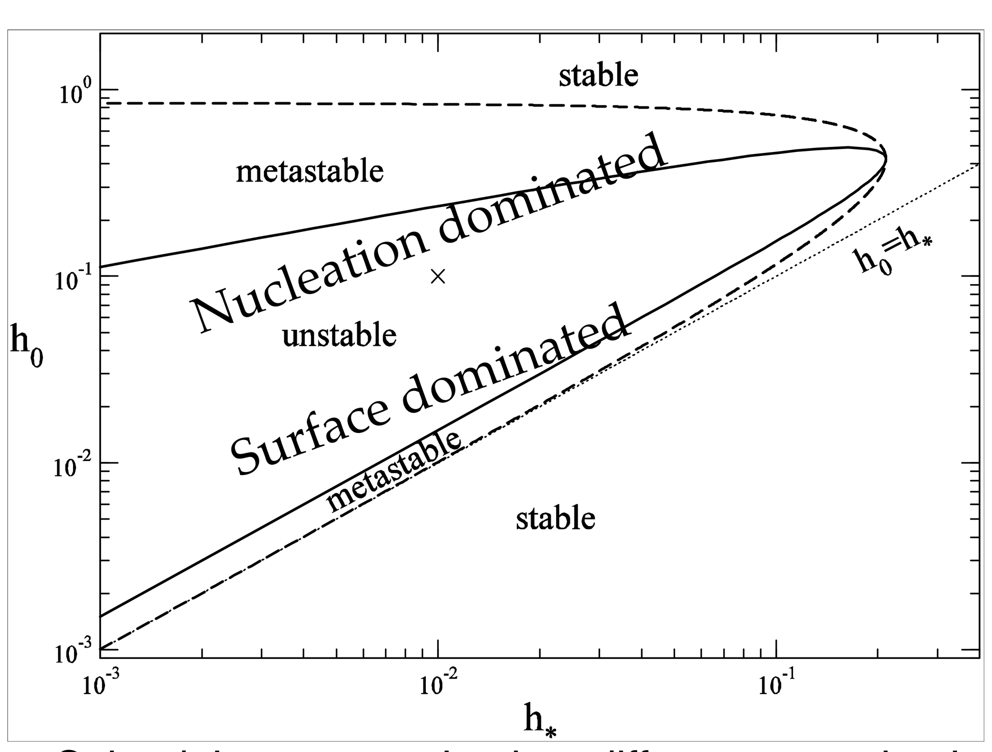
`Macro' Scaling:

$$h_c = x_c = a = \sqrt{\frac{\gamma}{\rho g}}; t_c = \frac{3\mu a}{\gamma}; D = 1; K = \frac{1-\cos\theta}{M h_*}$$

`Micro' Scaling:

$$h_c = h_*; x_c = \sqrt{\frac{M h_*^2}{1-\cos\theta}}; t_c = \frac{3\mu x_c^3}{\gamma h_c^2}; D = 0; K = 1$$

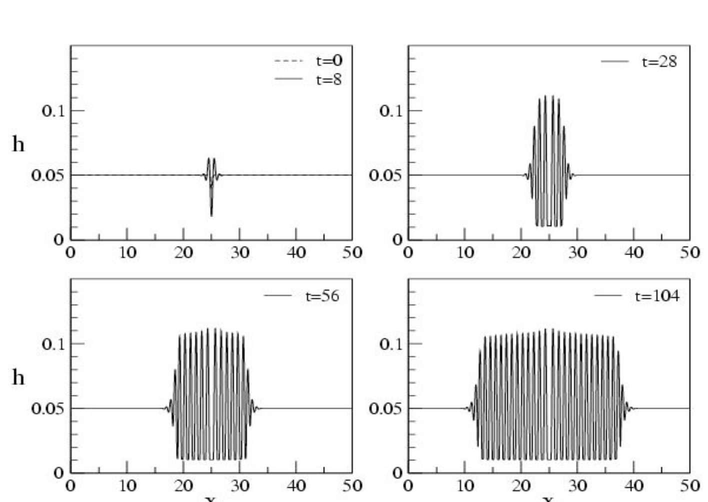
Infinite films: spinodal versus nucleation; stability, instability and metastability



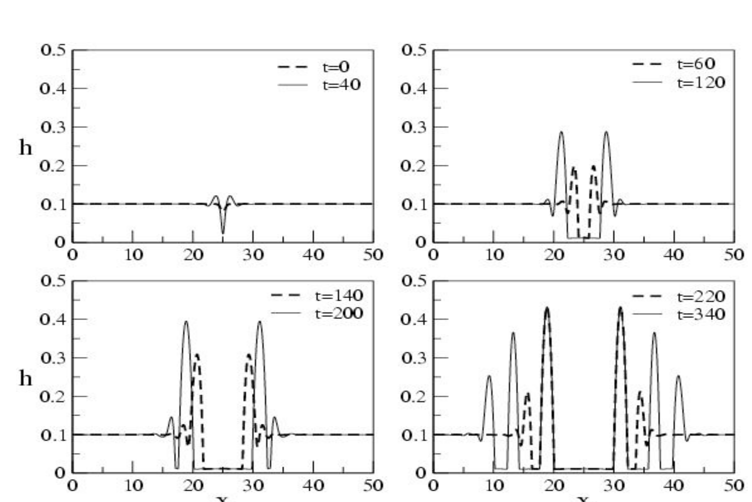
Linear stability analysis (LSA) results

Thiele etal, PRE 2001, ...

Spinodal versus nucleation: different emerging lengthscales resulting from finite size perturbations



Surface dominated: distance between the drops corresponds to LSA

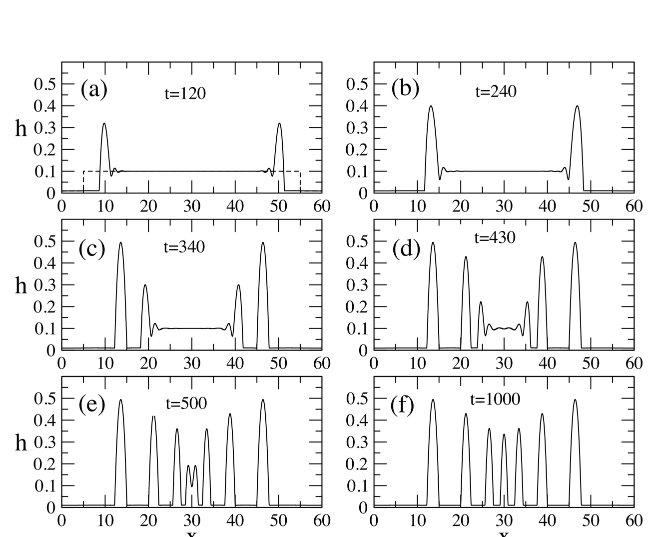


Nucleation dominated: distance between the drops does not correlate with LSA

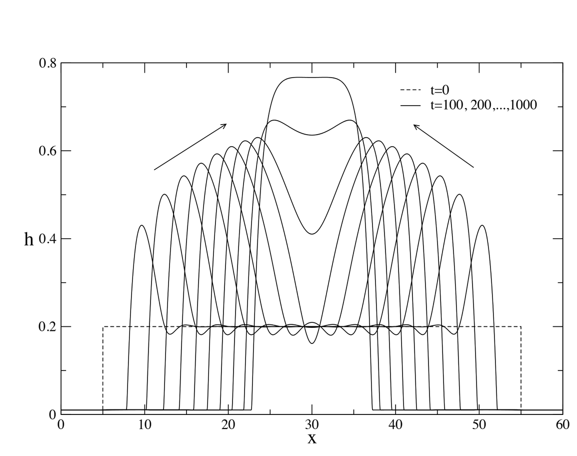
Metastable regime: unstable with respect to finite size perturbations

Finite versus Infinite Films

Influence of finite film size: acting as a finite size perturbation of an infinite film

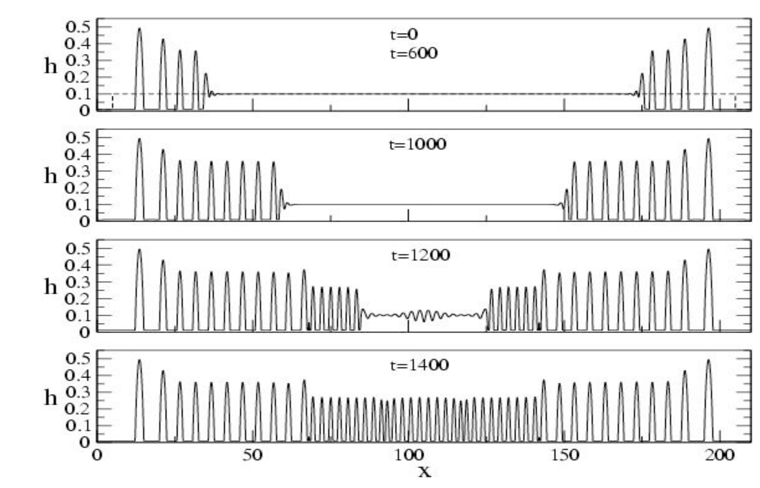


Linearly unstable (nucleation or spinodal)



Stable or metastable

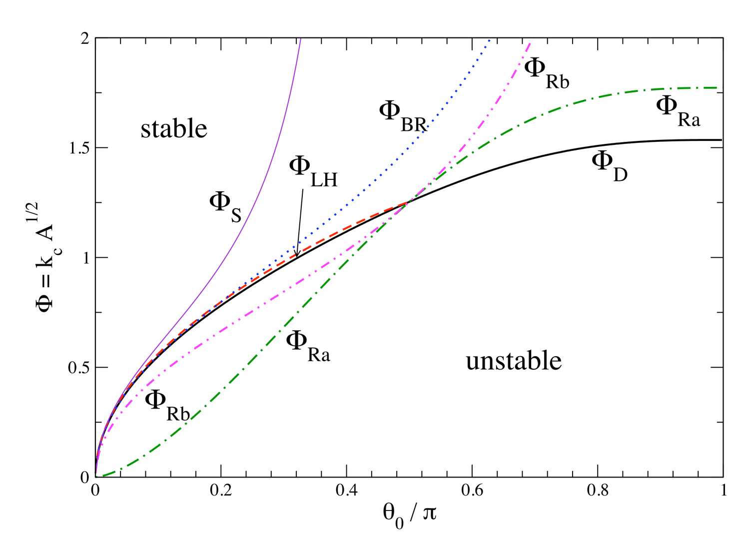
Interplay of two instability mechanisms: surface perturbations and end-driven instabilities: front propagation into unstable states
Distance between the patterns in nucleation regime determined by the relevant time scales of linearly unstable growth and instability propagating from the ends



An example where numerical noise in the central part of the film leads to length scales predicted by LSA [done in double precision; all other simulations carried out using quadrupole precision]

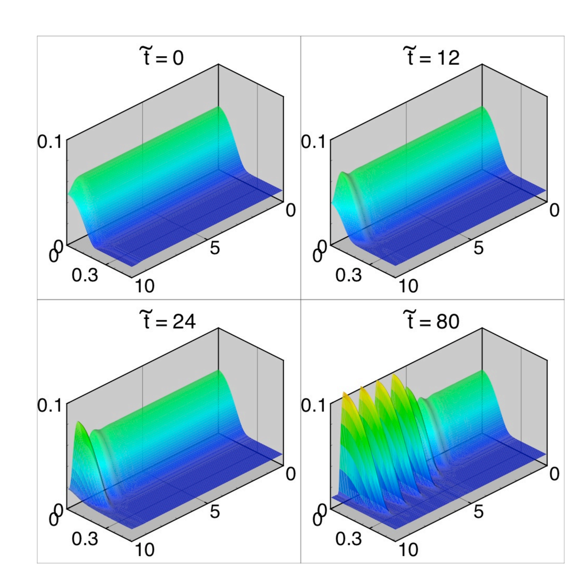
Rivulets versus Films

Differences between films and rivulets: curvature in the transverse direction; contact lines; increased instability

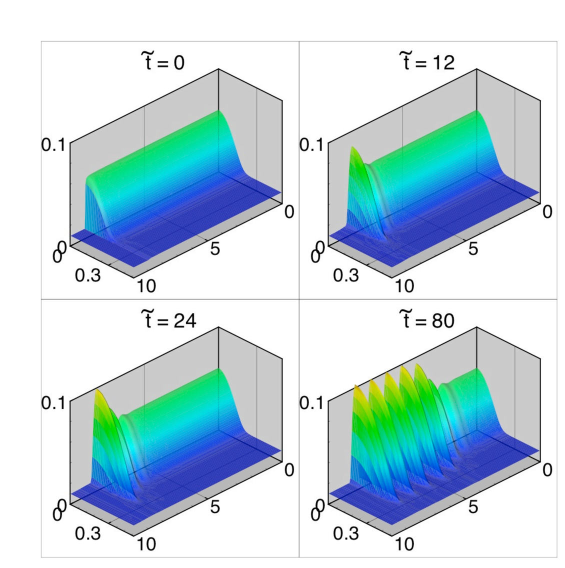


Interesting issues re comparison of various results in the literature:
Phi_D: Davis, JFM 1980, Langbein JFM 1990, Roy and Schwartz, JFM 1999
Phi_LH: Li and Homsy, PoF (2007)
Phi_BR : Brochard -Wyart and Redon, Lang. 1992
Phi_S: Sekimoto etal; Annals Phys. 1987
Phi_Ra - Rayleigh-Plato - use osculating circle radius
Phi_Rb - Rayleigh-Plato - use rivulet width

Finite size effects: no nucleation regime for rivulets: the emerging wavelengths in finite case correspond to the LSA
Main results: macro rivulets: importance of gravity
micro/nano rivulets: importance of liquid-solid interaction



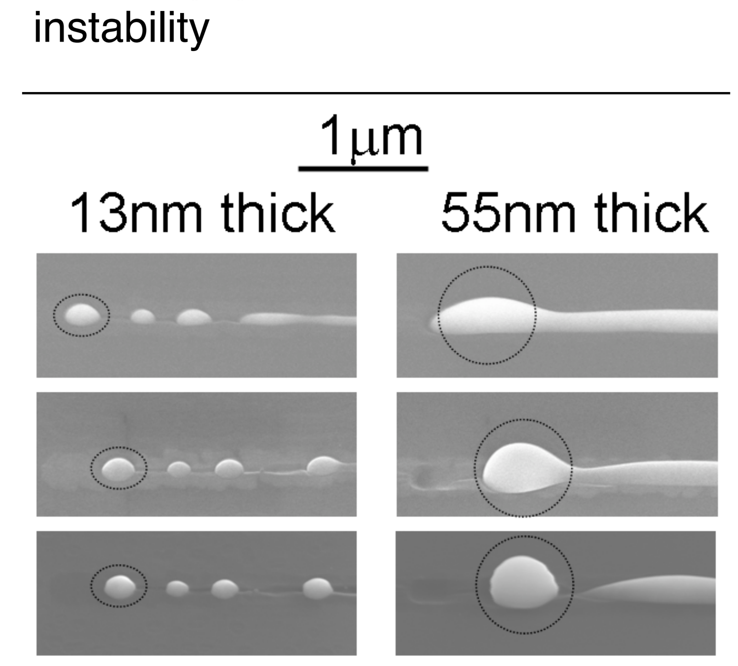
Infinite rivulet with finite size perturbation



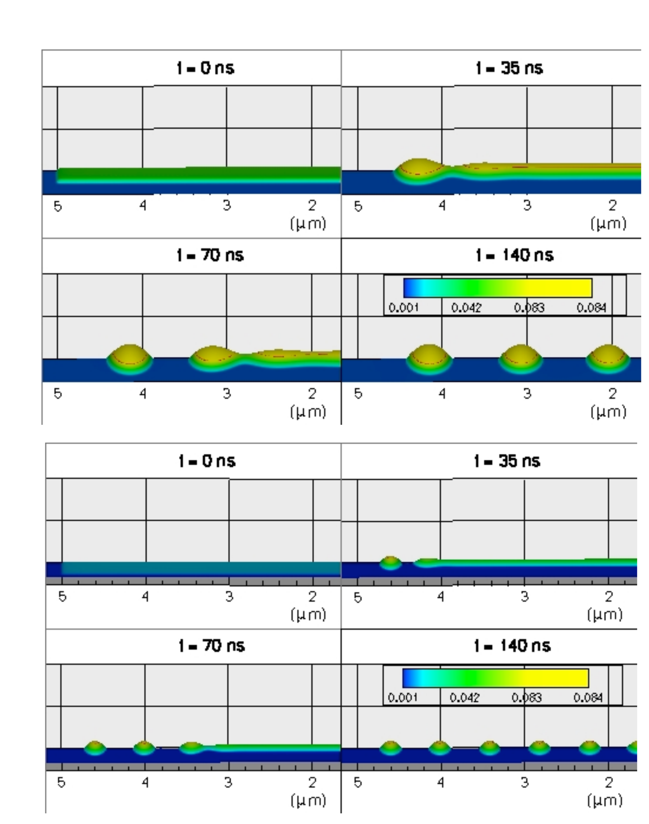
Finite rivulet (no perturbation)

Nano-scale laser- irradiated metal lines of finite length

Applications to nano-assembly
Experiments: repeated exposure of Ni lines to laser pulsing leading to repeated melting/solidification
Modeling ignores thermal effects and concentrates on the end-propagating instability



Experiment



13 nm

55 nm

Quantitative agreement between simulations and experiments suggesting that hydrodynamic approach is appropriate. Future work in progress.

Diez, J., Gonzalez, A., Kondic, L., On the breakup of fluid rivulets, submitted (2009).
Kondic, L., Diez, J., Rack, P., Guan, Y., Fowlkes, J., Nanoparticle assembly via the dewetting of patterned thin metal lines: Understanding the instability mechanism, Phys. Rev. E, **79**, 026302 (2009)
Diez, J., Kondic, L., On the breakup of fluid films of finite and infinite extent, Phys. Fluids,**19**, 072107 (2007)
Diez, J., Kondic, L. Computing three-dimensional thin film flows including contact lines, J. Comp. Phys., **183**, 274 (2002).