



# *ACIS Symposium on Nanobubbles*

Wednesday 4<sup>th</sup> December 2013  
Lecture theatre 2, School of Chemistry,  
The University of Sydney

This multidisciplinary symposium, supported by the Australasian Colloids and Interface Society (ACIS), will focus on recent developments in the understanding of nanobubble formation, stability and characterisation, with connections to experiments and applications. The Australasian Colloids and Interface Society was established in 2012 as an inclusive organization to bring together everyone in Australia and New Zealand (and beyond) who is interested in colloid and interfacial science, engineering and technology. To join ACIS, please visit <http://colloid-oz.org.au/>

## **Symposium Program**

13:00 Registration

13:30 Welcome and Introduction - Dr Chiara Neto, The University of Sydney

13:40 “*Experimental Studies of Nanobubbles at Solid-Water Interfaces*”;  
Xuehua Zhang, Department of Chemical and Biomolecular Engineering, University of Melbourne.

14:10 “*Surface nanobubbles: formation, universality of the contact angle, and stability*”;  
Detlef Lohse, Department of Applied Physics, University of Twente

14:40 “*A new theory of bubble growth and dissolution: implications for nanobubble stability*”;  
Vincent Craig, Department of Applied Mathematics, Australian National University

15:10 Tea break

15:40 Panel discussion

17:00 Closing remarks

18:00 Drinks and dinner at the restaurant Twelve, 222 King street, Newtown (Phone: 9519 9412), for those who would like to attend (not included in registration). This is in walking distance from the School of Chemistry.

*The coffee break is proudly sponsored by joint venture partners The Innovation Group and NewSpec.*

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## TALK ABSTRACTS

### Experimental Studies of Nanobubbles at Solid-Water Interfaces

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When a hydrophobic solid surface is in contact with water, gas bubbles as thin as  $< 100$  nm can form and stay for long time at ambient conditions. These nanobubbles have significant influence on a range of interfacial processes. For example, they give rise to hydrodynamic slip on the boundary, initiate the rupture of thin liquid films, facilitate the long-ranged interactions between hydrophobic surfaces, and enhance the attachment of a macroscopic bubble to the substrate. Experimentally, it is nontrivial to characterize such small fragile bubbles and unravel their fundamental physical properties.

Based on our established procedure, called the solvent exchange, for the nanobubble formation, we have systematically studied the formation, stability and response of nanobubbles to external fields (e.g. sonication and temperature rise). By following the bubble morphology by atomic force microscopy, we show the loss or gain of the nanobubble volume is mainly achieved by the change in the bubble height. The pinning on the three-phase boundary has significant implication on the properties of nanobubbles under various conditions. This talk will cover the effects of the substrate structures on the nanobubble formation, and the response of nanobubbles to the gas dissolution, the temperature increase, the extended gentle ultrasound and the substantial pressure drop in the environment.

### Surface nanobubbles: formation, universality of the contact angle, and stability

Detlef Lohse

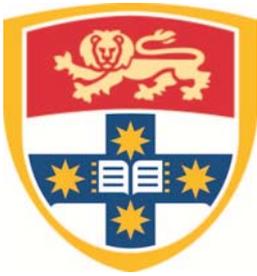
Physics of Fluids, Faculty of Science and Technology, University of Twente, The Netherlands

We study surface nanobubbles using molecular dynamics (MD) simulation of ternary (gas, liquid, solid) systems of Lennard-Jones fluids. They form for sufficiently low gas solubility in the liquid, i.e., for large relative gas concentration. For strong enough gas-solid attraction, the surface nanobubble is sitting on a gas layer, which forms in between the liquid and the solid. This gas layer is the reason for the universality of the contact angle, which we calculate from the microscopic parameters. Under the conditions of the MD simulations, the nanobubbles dissolve within less of a microsecond. So why then, under normal experimental conditions, are surface nanobubbles stable for many hours or even up to days rather than the expected microseconds? We present a theory that the limited gas diffusion through the water in the far field, the cooperative effect of nanobubble clusters, and the pinned contact line of the nanobubbles lead to the very slow dissolution rate.

References:

J. H. Weijjs, J. H. Snoeijer, and D. Lohse, Phys. Rev. Lett. 108, 104501 (2012);

J. H. Weis and D. Lohse, Phys. Rev. Lett. 110, 054501 (2013)



## **A new theory of bubble growth and dissolution: implications for nanobubble stability**

Vince Craig and Hongjie An

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Nanobubbles remain a controversial field of investigation. The main controversy surrounding nanobubbles is their lifetime. The classic work of Epstein and Plesset<sup>1</sup> (EP) from 1950 and the later work of Ljunggren and Eriksson<sup>2</sup> (LE) predict that nanobubbles of the size commonly observed by Atomic Force Microscopy should dissolve in less than a second. In contrast the experience of researchers across the world is that such bubbles are typically stable for periods of tens of minutes to several days.

The theory of EP and LE, whilst mathematically different, are based on the same physical principles. The model is that for a shrinking bubble, a high concentration of gas adjacent to the bubble surface relative to the bulk drives a diffusion process, whereas for a growing bubble the diffusion process is reversed. A necessary step is to determine the concentration of gas adjacent to the bubble. To do this EP use Henry's law in combination with the Laplace pressure. The Laplace pressure is used to determine the pressure within the bubble and this pressure is used in Henry's law to describe the solubility of gas adjacent to the bubble. Plesset was a highly respected scientist and the large and active fluid mechanics community use this approach to describe bubble dissolution and growth in a great number of papers. This approach is seen as standard in the field and is unquestioned.

Our theory rejects this approach. Rather the Ostwald equation is used to describe the solubility of a gas bubble. During this presentation I will show that a thermodynamic derivation of the Ostwald equation implicitly includes the Laplace pressure and shows that the driving force for dissolution is the surface tension and this effect increases as the surface to volume ratio of the phase increases as it does when an object becomes smaller. I will also attempt to explain why the Henry's Law-Laplace Pressure approach fails.

The new theory is described and predictions of the theory are compared to observations of the shrinkage or growth of nanobubbles and other bubbles showing good agreement. If time permits, some further implications of this new theory of bubble growth and dissolution will also be explored and it will be shown how the theory explains a number of observations of nanobubbles and other bubbles that are impossible within the framework of the EP theory.

The conclusion is that nanobubbles are long-lived due to kinetic stability and this implies that they are likely also present in bulk.

(1) Epstein, P. S.; Plesset, M. S. *Journal of Chemical Physics* 1950, 18, 1505.

(2) Ljunggren, S.; Eriksson, J. C. *Colloids and Surfaces a-Physicochemical and Engineering Aspects* 1997, 130, 151.



### List of Symposium participants

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#### Symposium Chair DR CHIARA NETO

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