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## Basic and applied researches in microgravity/Recherches fondamentales et appliquées en microgravité

# Aqueous foams and foam films stabilised by surfactants. Gravity-free studies

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## ABSTRACT

There are still many open questions and problems in both fundamental research and practical applications of foams. Despite the fact that foams have been extensively studied, many aspects of foam physics and chemistry still remain unclear. Experiments on foams performed under microgravity allow studying wet foams, such as those obtained early during the foaming process. On Earth, wet foams evolve too quickly due to gravity drainage and only dry foams can be studied. This paper reviews the foam and foam film studies that we have performed in gravity-free conditions. It highlights the importance of surface rheology as well as of confinement effects in foams and foam films behaviour.

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## 1. Introduction

Foams are dispersions of gas bubbles in liquids or solid matrices [1]. They occur widely in nature and are used in important industrial processes and commercial applications [2,3]. Liquid foams are an essential part of gas/liquid contacting processes such as distillation and flotation of minerals. Foams made with aqueous surfactant solutions are widely used for detergency purposes, while foams made with protein solutions are the base of many food products. Other applications of liquid foams include cosmetics, fire-fighting, oil recovery, and others. Solid polymeric foams, such as polystyrene and polyurethane, find applications as insulation panels in the construction industry and as packing and cushioning materials. Solid foams can also be made of metals, nowadays used in car and space industries.

Foams are usually prepared with liquid matrices. Because of the large density difference between air and the liquid, this liquid drains rapidly due to gravity and *dry* foams are obtained. Great progress has been made over the last thirty years in making the science of dry foams a sound and systematic discipline, with theories based on well-defined models being compared with well-characterised experiments. Properties of interest have included: the details of foam *structure* (shapes and arrangements of bubbles), capillary and gravity driven *drainage*, *rheology*, *coarsening* due to diffusion of gas (growth of large bubbles, shrinkage of small ones) and *coalescence* due to rupture of the films between bubbles [1,3].

Foam dynamics involves a variety of phenomena occurring at different length scales: molecular (monolayers of surface active agents at the air–water interface, thickness  $\sim 1\text{--}10$  nm), mesoscopic (films between bubbles, thickness  $\sim 10$  nm– $1$   $\mu\text{m}$ ), and macroscopic (bubbles and channels between bubbles called *Plateau borders*,  $\sim 100$   $\mu\text{m}$ – $1$  cm). These phenomena occur at different timescales, typically microseconds to hours. Furthermore, coarsening and coalescence are coupled with gravity drainage and are faster when the foam liquid fraction is lower. Due to this complexity, we still know little about coarsening and coalescence, a serious drawback for the prediction of dry foam stability. The study of the be-

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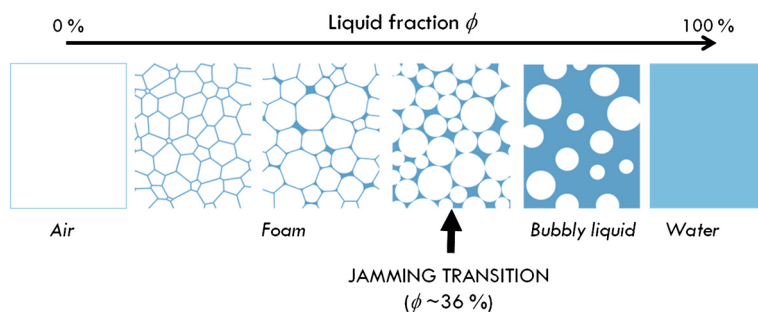


Fig. 1. Scheme of foam aspects for different liquid volume fractions  $\phi$ .

behaviour of the foam in the early stages, when it still contains large amounts of liquid, remains still more elusive. As a consequence, it is difficult to predict what will be the final foam structure although this knowledge would help to better target the applications.

All these open questions have motivated foam investigations in microgravity. Microgravity is indeed a helpful tool to suppress drainage and gain more insight into the coarsening and coalescence mechanisms and into the behaviour of wet foams. In this paper, we will briefly summarise the work that we have done over the years thanks to the support of CNES, in order to elucidate aqueous foams and foam films behaviour. We will focus on aqueous foams stabilised by surfactants. Part of this work has also been supported by ESA through a MAP program. Various experiments were performed in gravity-free conditions; others are scheduled in the near future. In the following, we will first recall some general concepts in foam science, then describe the different experiments and end with the plans for the near future.

## 2. General concepts for foams

The liquid volume fraction in foam,  $\phi$ , may vary from less than one percent (*dry foam*) to more than 10% (*wet foam*) (Fig. 1). At low liquid fractions, the bubbles are deformed into polyhedra with both quasi-flat faces (bordering films) and curved faces (at the edges). When  $\phi$  is larger than a critical value  $\phi_c$  ( $\sim 35\%$  for disordered foams and 25% for ordered ones), the bubbles are spherical and move independently; in this case, the term *bubbly liquid* is used instead of foam. An interesting transition occurs at  $\phi_c$  where the foam changes from solid-like (finite shear modulus  $G$ ) to liquid-like (disconnected bubbles). This is the *jamming transition*, also encountered in other assemblies of randomly packed objects, such as emulsions, sand, clays, etc., and presently the object of numerous studies [4].

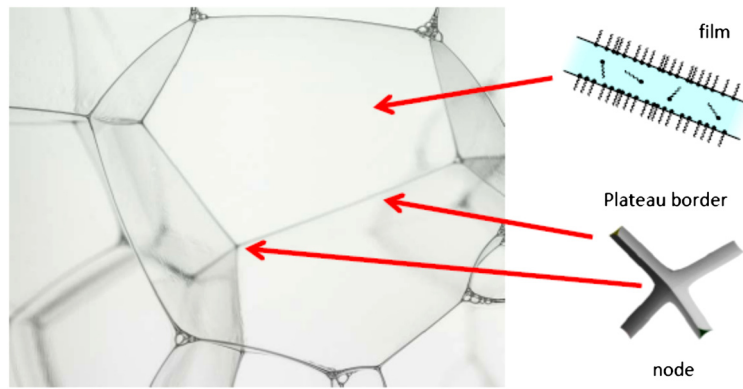
In order to generate a foam, an energy is needed to create the bubble surfaces, equal to  $\gamma A$ ,  $\gamma$  being the surface tension and  $A$  the area created. This energy is orders of magnitude larger than thermal energies and is not minimised: as a consequence, liquid foams are thermodynamically unstable. However, metastable configurations can be produced, in which each bubble takes a shape having minimal area for the given configuration: spheres for isolated bubbles and polyhedra (like the well-known tetrakaidecahedron proposed by Kelvin) in foams with small liquid volume fractions. Most of the liquid is confined to the edges called *Plateau borders* (PB), connecting three films and junctions or *nodes* connecting four PBs (Fig. 2).

Because liquid foams are metastable, the use of stabilising agents is required, which are generally surfactant molecules (Fig. 2), but polymers, proteins or particles can also be used. The stabiliser role is to slow down the different mechanisms of foam ageing: drainage, coalescence and coarsening. After formation, foams evolve with time until they fully disappear, typically a few hours later with surfactant foams. The foam destruction starts with the rupture of foam films, hence foam films have also been extensively studied in link with foam stability.

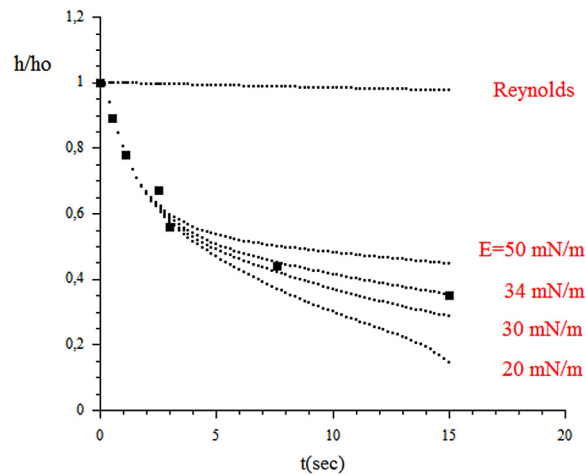
## 3. Experiments on foam films

We started our studies with model foam films, an activity supported by CNES in the 1990s. It was easy in this case to simulate microgravity conditions by studying horizontal films. We constructed devices similar to those proposed by Sheludko [5] and Mysels [6], later called *thin film balances* (TFBs). In the Sheludko device, horizontal films are formed in capillaries connected to a liquid reservoir of controlled hydrostatic pressure. The film thickness is measured by optical reflectivity. The Mysels' device is similar, but it makes use of a porous plate instead of a capillary tube, allowing accessing much larger pressures. In both cases, the pressure in the film holder is lower than the pressure in the film centre by a quantity  $\Delta P$ . As a result and despite the absence of gravity force, the films drain because of the imposed pressure difference  $\Delta P$ . Note that horizontal foam films also drain, because in this case, the pressure difference is the capillary pressure arising from the PB's curvature (Fig. 2). This type of drainage is called *capillary drainage*.

After drainage in a TFB, the film reaches an equilibrium thickness  $h$  at which the applied pressure is equal to the force between film surfaces counted per unit area, also called *disjoining pressure*  $\Pi_d$  (for a recent review, see [7]). TFBs therefore allow measuring disjoining pressures, an important property controlling foam stability (for a recent review, see [8]). Note that only repulsive forces can be measured with TFBs, at the difference of the well-known atomic force microscopy (AFM) instruments.



**Fig. 2.** Aqueous dry foam picture. Liquid films separate the sides of the bubbles, Plateau borders and nodes are seen at their corners. The liquid films are stabilised by surfactant monolayers, surfactant molecules being represented by a circle (polar head), in contact with water, and a hydrophobic chain, in contact with air. Surfactant molecules are also present in the bulk liquid.



**Fig. 3.** Black squares: relative film thickness versus time. Upper dotted lines: calculated thicknesses according to Eq. (1). Lower dotted lines: calculated thicknesses for different surface compression moduli. Adapted from ref. [9].

The velocity of film drainage  $V_f$  can be calculated assuming that the film surfaces are flat, parallel and immobile. In such a simple case, an expression derived by Reynolds for the flow between two rigid plates brought together under the action of a constant pressure can be used:

$$V_f = -\frac{dh}{dt} = \frac{h^3}{3\eta r^2} \Delta P \quad (1)$$

where  $h$  is the film thickness,  $r$  the film radius and  $\eta$  the liquid viscosity. However, the film surfaces are not solid, as assumed in the derivation of Eq. (1), and surface flow can arise. Our numerical calculations done in the simple case of a flat parallel film covered by surfactant monolayers showed that the influence of surface rheology, in particular the surface compression elastic modulus  $E$ , can be very important for thick enough films [9] (around  $1 \mu\text{m}$ ) (Fig. 3). Let us recall that the modulus  $E$  allows us to quantitatively describe the Marangoni forces, i.e. the surface tension gradients due to surface concentration gradients arising during the flow [10]. Fig. 3 shows that  $V_f$  increases when  $E$  increases, but that for typical  $E$  values for surfactant monolayers (a few tens of  $\text{mN/m}$ ), film drainage is much faster than predicted for fully immobile surfaces (Eq. (1)). We have also shown that the surface elastic modulus that needs to be considered is the intrinsic modulus  $E$ , not the one measured on surfactant solutions with low-frequency excitation, which is lower, due to surfactant exchanges between surface and bulk. Indeed, in the film, surfactant is taken away along the surface to the Plateau borders and there is not enough surfactant in the liquid film to replenish the surface. These results highlighted the importance of liquid confinement in foam films.

When the surfactant solution is above the critical micellar concentration ( $cmc$ ), film drainage becomes more complex. This drainage occurs stepwise, due to the presence of surfactant micelles which form layered structures under the film surfaces: drainage proceeds by expulsion of the layers, one after the other, into the film border [11]. The process is another consequence of confinement, this time resulting in oscillatory surface forces. We have evidenced such oscillatory forces



**Fig. 4.** Forced drainage experiments in parabolic flights: picture of a foam at three different times, evidencing isotropic diffusion. The liquid is injected at the centre, the wires are connections to electrodes; note that the wetter foam appears dark. Adapted from ref. [20].

with our TFB, using foam films containing polyelectrolyte solutions: in this case, the oscillatory forces arise because of the electrostatic repulsion between polymer chains [12]. Our work on film stratification continued in parallel with foams studies started in the mid-1990s, which are supported by CNES and ESA since 2000. We have in particular established a theory for the kinetics of film stratification [13] and applied this knowledge to measure local viscosities in films of nanometric thickness [14].

More recently, we have undertaken studies of surfactant stabilised vertical films during their withdrawal from a surfactant solution. As in horizontal films, an influence of the confinement was evidenced: the thickness of the withdrawn film increases with withdrawal velocity until a limit thickness  $h^*$  is reached. Above  $h^*$ , the amount of surfactant in the film is sufficient to replenish the film surfaces during the flow, and the surface tension gradient that equilibrates the hydrodynamic force vanishes [15].

## 4. Experiments on foams

### 4.1. Foam drainage

Gravity plays an important role in the formation of foam and its subsequent evolution. Its primary effect is to cause excess liquid to drain rapidly away. When the foam is stable enough, it becomes dry and the gravitational force is balanced by a vertical pressure gradient in the liquid leading to a vertical profile of liquid fraction [16]. The liquid volume fraction  $\phi$  at the top of the foam are typically smaller than a few percent.

The addition of liquid at the top of such a dry foam results in a solitary wave with an approximately constant profile during its downward passage, the process being called *forced drainage* [1]. When we started our first foam studies, there were two theories of forced drainage, one assuming rigid surfaces and the other mobile interfaces, without obvious reason allowing deciding which one was correct. We showed that in fact, one can encounter a variety of intermediate situations, depending on surface rheology [17]. The drainage models now include a mobility parameter  $M$ , usually identified with the inverse Boussinesq number  $B = \eta_S/\eta R$ ,  $\eta_S$  being the surface shear viscosity and  $R$  the mean bubble radius [18]. Note that the surface compression modulus  $E$  does not play a role in foam drainage. Indeed the main liquid flow occurs in PBs and nodes, which are too wide for confinement effects to play a role (surfactant exchanges between surface and bulk are possible and the surface tension gradients vanish).

Forced drainage can be used to study wet foams, but only up to about  $\phi = 20\%$ , beyond which various dynamic instabilities (primarily convection) occur [19]. We have undertaken parabolic flight (PF) experiments in order to study wetter foams. In microgravity where only capillary effects are present, the liquid flow in a foam resembles the one in plants and tissues: capillary pressure gradients can induce a diffusive fluid transport, coupled with macroscopic strains via the elasticity of the solid matrix (foams are poro-elastic materials, the shear elastic modulus  $G$  being of order  $\gamma/R$  [1]). In parabolic flights, dry foams were produced during the hyper gravity period, after which the liquid was injected in the foam and its propagation studied. We monitored the variations of the liquid fraction  $\phi$  in time and space, by coupling electrical conductimetry and light transmission [20]. In Fig. 4, one sees that the liquid front propagation in the dry foam is isotropic under microgravity conditions (different from Earth, where the liquid moves more quickly in the vertical direction). This is because in microgravity, capillarity is the only driving force for drainage.

Theoretical aspects of forced drainage experiments in microgravity have been discussed in ref. [21], starting from the drainage equations developed for Earth-based experiments. In agreement with the simulations, experiments showed that there is a well-defined maximum distance  $d$  covered by the injected fluid which is proportional to the square root of time, the prefactor depending on the surface mobility  $M$ . At the high liquid fractions created in microgravity conditions ( $>20\%$ ), it was found that the classical drainage models fail, as some of their basic assumptions are no longer valid (in particular, the volume of the nodes is no longer negligible) [20].

### 4.2. Foam rheology

Before 2007, the aim of the MAP project was the construction of an instrument dedicated to the study of foam rheology in the ISS. As mentioned earlier, foams change at the jamming transition ( $\phi = \phi_c$ ) from solid-like (finite shear modulus  $G$ ) to



**Fig. 5.** Astronaut Frank de Winne on the ISS. A rack containing the foam samples is free floating in the centre of the picture. A second rack is placed in front of a computer screen for backlight illumination during video recording. Photo: ESA.

liquid-like (disconnected bubbles). Liquid fractions close to  $\phi_c$  cannot be accessed easily on Earth, restricting most rheology experiments to dry foams. Existing experiments with wet foams were performed using viscous liquids which slow down drainage [22] or thin layers of bubbles in which drainage is not significant [23].

Laboratory experiments were however undertaken aiming to investigate the possible influence of surface rheology, which was not considered in previous works. In order to control foam slip at the surfaces of the rheometer plates, we used both smooth and roughened plates. We therefore imposed flows dominated either by slip or by shear, respectively. We showed that viscous dissipation arises both in films and PBs, giving rise to different regimes, the transition between them being controlled by the surface mobility  $M$  and the liquid fraction  $\phi$  [24].

A special microgravity cell was first designed to perform both drainage and rheology studies in the International Space Station (ISS). The cell was cylindrical, with top and bottom plates able to rotate either simultaneously (to study drainage) or to remain independent, the lower plate remaining fixed (to study rheology). The cell possessed a suitable combination of two types of diagnostics, conductivity and multiple light scattering. A Maxus flight performed in 2005 allowed us to obtain preliminary drainage data [25]. The cell design was subsequently abandoned due to its elevated cost.

#### 4.3. Bubble coalescence

When drainage proceeds, the films between bubbles become thinner and can rupture, leading to bubble *coalescence*. So far, very little is understood about the main mechanisms of film rupture. Studies have suggested that coalescence in foams occurs once critical values of bubble sizes [26], liquid fraction [27,28] and/or applied pressure (or capillary pressure) are reached [29,30]. Even if the mechanisms invoked are different (disjoining pressure, concentration fluctuations in the surface layers, dynamics of bubble rearrangements during coarsening), it is difficult to discriminate experimentally between them; in particular, capillary pressure, liquid fraction, bubble sizes are linked and change with time due to drainage and coarsening. The different behaviours observed in the literature might also be due to different flow conditions and accordingly to different coalescence processes. We have shown in particular that the rupture of entrained soap films is deterministic [31], at the difference of the rupture of equilibrium films [32]. A discussion of this complex issue can be found in ref. [8].

On Earth, the lifetime of foam is affected by drainage: when the bubbles become closer, the liquid films eventually break, and the foam collapses. In microgravity, gravity drainage is absent and one could wonder if foams containing large amounts of liquid are more stable. An investigation opportunity was offered to us through the ESA educational program with access to the ISS in 2009 and 2012. Complementary experiments were performed during parabolic flights.

##### 4.3.1. Surfactant foams

We have compared the stability of aqueous foams made with various surfactants both on Earth and in the ISS (see Fig. 5) [33,34].

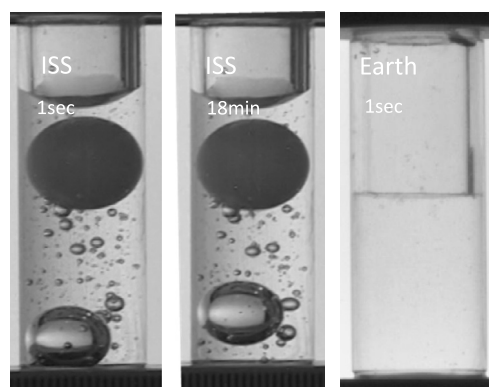
Generally, the foamability was found much larger on the ISS than on Earth. A striking result is that solutions that foam little on Earth lead to significant amounts of foam in space. Moreover, the foams showed a remarkable stability in the ISS. The foams were quite wet, with liquid fractions  $\phi$  of 30%. The bubbles had a quasi-spherical shape which slows down capillary drainage, coarsening and coalescence.

##### 4.3.2. Surfactant free foams

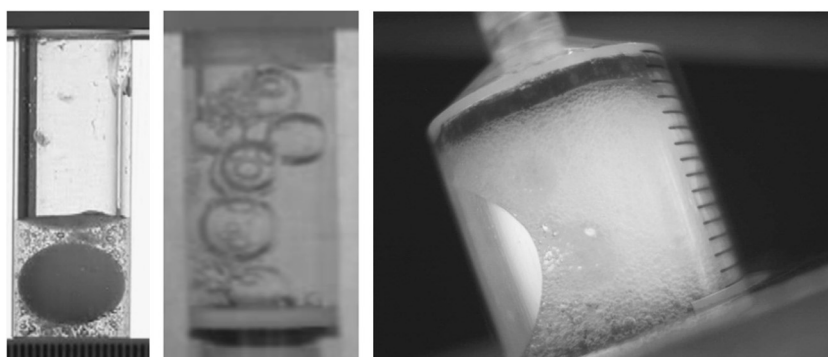
Fig. 6 shows an example of bubbly liquids made with pure water. Once formed, the bubbles remained stable over long periods of time in microgravity conditions. They may move somewhat, but not enough to coalesce (Fig. 6, left). This is due to the absence of drainage: bubbles stay sufficiently far apart, avoiding coalescence. On Earth and in the same conditions, the water does not contain any bubbles (Fig. 6, right).

Complementary studies have been performed in PFs [35] and are fully consistent with ISS studies. In parabolic flights, we used foaming devices allowing creating foams with various liquid fractions. In one device, the liquid and air are rapidly pushed back and forth through a constriction between two syringes. In another device, a porous plate moves back and forth in a cylinder containing liquid (*mighty whipper*). In the ISS, less gas could be incorporated in the liquid, because the energy involved in the mixing procedure was much lower; as a consequence, the liquid volume fraction remained large (Fig. 7).





**Fig. 6.** Left: water samples made in the ISS, 1 s and 18 min after shaking; the bead visible in the figure is used to enhance bubbles production during shaking in the small space between the bead and the liquid container. Right: pure water on Earth, 1 s after shaking in the same conditions (the bead cannot be seen as it has fallen in the bottom of the tube). Pictures from [35].



**Fig. 7.** Pure water foams made in microgravity with liquid/air volume ratio of 30%; Left: ISS, bead-cylinder device. Middle: PF, two-syringe system. Right: PF, mighty whipper. Pictures from [35].

Surprisingly at first sight, we could not generate water foams with  $\phi < \phi_c$ . Fast-coalescence events were observed as soon as the bubbles came close to each other whereas such events are absent in the bubbly state ( $\phi > \phi_c$ ). We proposed the following explanation: when  $\phi < \phi_c$ , the bubbles are distorted and films form. These films thin because of capillary drainage, despite the absence of gravity drainage, as demonstrated in earlier PFs (§4.1). Thinning of pure water films is extremely fast and is followed by film rupture, as on Earth. As a result, stable foam with polyhedral bubbles is not formed from pure water, even in microgravity.

We also made foams with different ethanol–water mixtures in the ISS [34]. On Earth, no foam is created upon shaking, but foams can be obtained by constant bubbling [36]. As on Earth, the amount of foam created is different for all the samples, those from the liquids that foam less on Earth giving rise to the smallest amount of foam in microgravity. This is likely because during foam formation, encounters between bubbles are frequent due to the convective motion. Because the liquids used are poor foamers, coalescence rapidly follows these encounters. The differences observed when changing the ethanol concentration were attributed to surface tension gradients which were maximum in the concentration range 10–20% ethanol [36]. As discussed in §3 (see curves for increasing  $E$  in Fig. 3), these gradients slow down film gravity drainage and enhance foam lifetime. In microgravity, only capillary drainage remains, and film thinning is slower. However, it remains controlled by the surface tension gradients, hence the amount of foam is higher for the same alcohol concentrations than on Earth.

#### 4.3.3. Antifoams

There are many instances where foams are unwanted and need to be controlled or destroyed, such as in washing or fermentation processes. Antifoam agents are then used to break the films between bubbles [37]. They are also used to control the amount of films in solid foams during the solidification of the precursor liquid foams. The elastic properties of the solid foams can thus be finely tuned for specific applications.

Foaming experiments were carried out on Earth, in the ISS and in parabolic flights to test the efficiency of an antifoam (AF). The experiments made use of a surfactant solution that foams very well and of a commercial antifoam (a dispersion containing hydrophobised silica particles mixed with oil). The ISS studies showed that AF was completely ineffective in very wet foams [34]. In the PF studies, we varied the liquid fraction  $\phi$  [38]. Fig. 8 shows the case of a drier foam with  $\phi = 10\%$ . The samples with no AF foam rapidly and are stable for the duration of the experiments. It also confirms that on Earth, AF is

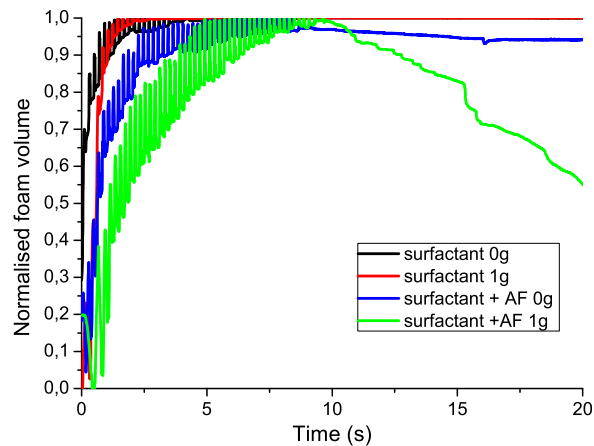


Fig. 8. Normalised foam volume versus time; liquid fraction  $\phi = 10\%$ . Adapted from [38].

effective at breaking the foam both during generation and afterwards. In microgravity, AF is still effective during generation, although less so than on Earth, but it is very ineffective after generation.

We had shown in ISS studies that even fast AFs can be completely ineffective if no films are present [34]. When the liquid fraction is above random close packing ( $\phi > \phi_c$ ), the bubbles remain spherical and no films are present. This explains why the AF is ineffective, since it acts by breaking the films. When  $\phi < \phi_c$ , a more subtle explanation has to be looked for. Straight after generation, the antifoam globules are likely evenly distributed throughout the foam in films, PBs and nodes. After film drainage, most of the AF find themselves in PBs. To continue to be effective, the AFs now have to make their way back towards the films to break them. On Earth, the particles move within the PBs because of drainage, buoyancy (AF density is not the same as water) and diffusion. In microgravity, only diffusion remains, and we have shown that their transport towards the films is too slow to break these films.

This discussion highlights the importance of the transport step, which despite the extensive work carried out on AF mechanisms is discussed very little in the literature. It shows that buoyancy plays a significant role in the transport of AF in the Plateau borders. This result can also explain the 20-year-old mystery [39] of the inefficiency of AF on Earth when their size is below a few microns: they are too small for buoyancy to work efficiently.

#### 4.4. ISS future experiments: foam coarsening

Coarsening involves the transport of gas between bubbles of different sizes due to pressure differences, leading to the growth of the average bubble radius  $R$  with time,  $t: R \sim t^{1/2}$  [1,3]. Coarsening has the same origin than the phenomenon of Ostwald ripening in bubbly liquids, where the gas diffuses from the smaller to the larger bubbles due to difference in Laplace pressure. In the latter situation however,  $R \sim t^{1/3}$  [40]. The law  $R \sim t^{1/2}$  arises from the fact that in foams, the gas mainly diffuses through the thin films between bubbles for which the diffusion path is the smallest. The scaling laws for coarsening and Ostwald ripening are well established, but the pre-factors are difficult to evaluate. In the coarsening case, the foam is made of polyhedral bubbles and the evolution of single bubbles with different number of faces,  $N$ , is different (some grow, others shrink depending on  $N$ ) [41]. The characteristic coarsening time can be written as:

$$t_{\text{coars}} = \frac{R^2}{D_{\text{eff}} f(\phi) h} \quad (2)$$

where  $D_{\text{eff}}$  an effective diffusion coefficient and  $f(\phi)$  the fraction of total area  $A$  of the bubble covered by thin films and  $h$  the film thickness [42]. The diffusion of gas molecules through thin films might be affected by the presence of surfactant monolayers, which contribution can be significant, when their surface compression modulus  $E$  is high. When  $E$  is larger than about  $\gamma/2$ , coarsening is arrested, as observed in foams stabilised by particles [43]. In the case of foams stabilised by surfactants, coarsening being an extremely slow process, the confinement effects responsible of the large value of  $E$  no longer hold (surfactant has time to diffuse from the PBs and to adsorb at film surfaces). We have shown that the differences in coarsening times observed between surfactants are likely due to differences in film permeability, which is not simply proportional to  $h$  as in Eq. (2), but is affected by the presence of the surfactant monolayers [44]. In the case of bubbly liquids,  $t_{\text{coars}}$  is proportional to  $R^3$ , inversely proportional to another effective diffusion coefficient, and is also dependent on the liquid volume fraction [40].

On Earth, foam coarsening is frequently coupled with foam drainage, and the coupling is not easy to account for [18]. Microgravity conditions are therefore ideal to study the coarsening process. After 2007, the MAP project was re-oriented towards a foam coarsening study. Foams with very small bubble sizes will be prepared, and the coarsening will be studied using multiple light scattering techniques. Note that experiments with magnetically levitated foams were performed recently

and evidenced a transition between the regimes  $R \sim t^{1/2}$  and  $R \sim t^{1/3}$  [45]. This paves the way for understanding coarsening in perfect gravity-free conditions.

The project will also provide new insight about the intermittent rearrangements of the packing structure induced by the diffusive gas exchange between neighbouring bubbles. These rearrangements were recently studied in thin layers of bubbles in order to minimise the effect of drainage [46]. The shear elastic modulus of wet foams should vanish at the jamming transition, and it is expected that the structural relaxation times will become very large. Insight about rearrangement dynamics in wet foams will therefore help to prepare the rheology study of foams close to the jamming transition. An ISS module is being constructed and the flight is scheduled at the end of 2017.

## 5. Conclusions

We have shown that foams stable on Earth were also stable in microgravity, the foamability and foam lifetimes being substantially increased. More strikingly, foams unstable on Earth become stable in microgravity: this is because gravity drainage is suppressed, capillary drainage is slowed down due to the quasi-spherical shape of the bubbles, coarsening is also slowed down because the films between bubbles remain thick, inhibiting coalescence as well. Bubbly water is even very stable, but foams with polyhedral bubbles cannot be obtained because of the very rapid capillary drainage of films. Solutions that are difficult to foam on Earth also require more vigorous shaking in microgravity, and water is no exception. Antifoam agents are even ineffective due to the large film thickness and to the absence of buoyancy.

Capillary imbibition of foams has been studied in parabolic flights. A good agreement with theory and simulation was found at low liquid volume fraction, but discrepancies were evidenced for the wetter foams. Extensions of the theories are needed in order to model this process, which is important for a variety of other poro-elastic materials such as plants and biological tissues for instance.

Coarsening of wet foams will be studied in a future ISS program. Microgravity experiments of wet foam rheology remain to be planned. The knowledge about rearrangement dynamics in wet foams gained during the coarsening experiments will however bring insights for the foam rheology close to the jamming transition.

Our studies highlighted the importance of surface rheology and of the confinement in thin foam films for the behaviour of surfactant foams, even in gravity-free conditions.

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