

# An interpretation of Rubinstein, Cohen & Fineberg's Detachment fronts using an analogy between asperities and bubbles

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## 1 Abstract

We suggest that Rubinstein et al (2004) "slow fronts" are the fronts of contact renewal of asperities, for which the average number of microcontacts is conserved, but any contact death is, on average, associated with the birth of a new fresh microcontact at an uncorrelated position. Considering a fraction of the energy is dissipated by as adhesive or viscoelastic processes, we use an analogy with the recent mechanism suggested by Chaudhurya-Kim for the velocity of propagation of bubbles in the sliding of thin confined films of rubber on a rigid plate, which is due to an elastic instability in the rubber layer. The analogy suggests that the process of formation birth and death of asperity contacts is the key to understand the friction detachment, as rate-state dependent friction already partly recognize. Using the same equations of the Chaudhurya-Kim bubbles, and correcting only for the different elastic modulus in the PMMA with respect to the rubber, shows surprisingly the asperity "slow fronts" are predicted to move at speed about one order of magnitude lower than the Rayleigh speed, as experimentally noticed in Rubinstein et al (2004). While we don't beleive there are "bubbles" strictly speaking, this striking result cannot be pure coincidence, and calls for more investigation.

## 2 Background

Rubinstein et al (2004) have shown interesting experiments where by looking indirectly at measurements of the local contact area in real time at very high speed, they could see detachment fronts, and in particular they found that the most important front (in terms of % of contact area detachment), was not due to sub-Rayleigh fronts and intersonic fronts, but of slow detachment fronts having a speed about 1 order of magnitude smaller than Rayleigh speed. This is important because it shows that clearly Coulomb's law (which predicts no change of contact area during sliding), and rate-state dependent friction (which predict only the high speed fronts, although expects the contact area to change due to the asperity population ageing-rejuvenation process), are inadequate to describe the most important process going on at the interface, which in turn they suggested could explain recent observations of slow or 'silent' earthquakes in which

significant slip was observed with a minimal acoustic signature. Unfortunately, not much data is available on whether the speed of the slow fronts depends on the applied stress, or on the driving velocity.

However, the 1 order of magnitude slower propagation calls for hysteretic effects. The first reaction is to think of "Schallamach waves" where "waves" could be considered an improper denomination, as normally wave are associated to very high speeds. Schallamach proposed in 1963 for dry rubber friction, a seminal dynamic state variable model, which remains the basis of all more recent theories of gel (Gong & Osada, 2002) and rubber friction (Charitat and Joanny, 2000, Chernyak and Leonov, 1986). The speed of Schallamach waves depends on viscosity of material, but also the sliding speed, and the applied stress. For example on elastomeric materials, the Rayleigh speed is of order of  $30m/s$ . "Schallamach waves" propagate at speeds at least 1000 times smaller. In the case of gelatin, contact is maintained in the sliding regions. Other non-homogeneous sliding has been observed (Roberts, 1976, Schallamach 1971) at some smooth soft rubber/glass interfaces. This occurs via propagating self healing pulses, consisting of regions of interfacial detachment with macroscopic opening which re-adhere at the back edge. So, in this regime, dissipation is essentially controlled by adhesion hysteresis (Barquins and Courtel 1975). Baumberger and Caroli (2006) however say *"Though high compliance and large viscoelastic losses are thought to promote this sliding mode, no prediction relating material properties to the dynamics, nor even to the occurrence of Schallamach waves is available up to now."*

A different mechanism has been found for sliding of a thin confined film by Chaudhurya and Kim (2007). They considered a rectangular glass prism sheared off a thin film of PDMS rubber bonded to a glass plate. The root mean square roughness of the glass prism was very small, found to be  $9nm$  over an area of  $20\mu m^2$  using an atomic force microscope. Elastic instability leads to the development of bubbles at the interface. Contrary to the case of the Schallamach waves which propagates from the rear to the frontal end of the slider in the sliding of a rigid object over soft elastomer, the Chaudhurya-Kim bubbles, move along the direction of sliding and they occur only in thin confined films, although they share the features of Schallamach waves (Schallamach 1971, Rand and Crosby, 2006) and slip pulses (Baumberger et al 2002) in that the propagations of all of these are driven by the gradient of shear strain energy.

### 3 Asperity contacts

Schallamach waves, Chaudhurya-Kim bubbles, and slip pulses, are *all* observed in systems where the material is very compliant, so that the real contact area is very close to the apparent one. At this scale, asperities do not have much role. Adhesion, adhesive hysteresis, have.

However, this is *not* the case of many other contacts, including the metal-to-metal contact, or even the contacts in geophysics.

Bowden and Tabor in Cambridge proposed in the 1940-50's the junction

theory (Bowden and Tabor, 1950), ie that the real contact area being a small portion of the nominal contact area,

$$\Sigma_r = A_r/A_{nom} \quad (1)$$

typically of the order of  $10^{-3}$ , and dictated by the plastic deformation and giving the linear law independent on the nominal shape of the surfaces in contact. Greenwood and Williamson (1966), also explained the linearity of contact area with load with a simple models of roughness, as an application in a sense of the Central Limit Theorem in statistics, so that assuming a general case relationship for the shear strength as a function of local pressure  $\tau(p)$ , the convolution integral leads to proportionality of the shear load to the normal load.

Baumberger and Caroli (2006) call those with asperities, Multi Contact Interfaces (MCI), and attribute the strengthening of MCIs static thresholds to the sole time dependence of the area factor  $\Sigma_r$  in Tabor's expression. They define geometric age of the interface  $\Phi$  related to the state variable of rate-state friction laws, and since, under constant normal load, the average number of microcontacts is conserved, any contact death is, on average, associated with the birth of a new fresh microcontact at an uncorrelated position, which has not yet experienced creep. Contact renewal therefore limits the age of the MCIs to the average lifetime of a given configuration of microcontacts, which can be written phenomenologically as:  $\Phi_{ss} = D_0/V$ . Geometric aging thus immediately appears as a candidate process for explaining the  $V$ -weakening behavior of the steady sliding dynamical friction.

From the phenomenological point of view, based on experimental observations, rate and state models of friction have reached the same conclusions, namely that friction needs a description of the local microprocesses of surface interaction through appropriately chosen state variables see e.g. Dieterich (1979), Ruina (1983), Rice and Ruina (1983).

Based on these laws, many attempts have emerged to deal with the frictional sliding process similarly to classic dynamic fracture theories of growing shear cracks in coherent interfaces separating identical monolithic solids, showing typically intersonic shear rupture (Rosakis 2002): in other words

- the interface is assumed to be smooth, despite the friction law was shown critically to depend on asperities;
- the rupture front is considered to be a distinct point (sharp tip crack), despite the process is clearly asperities rupture and renewal.

With these continuum studies, self-sustained slip pulse along an interface of deformable bodies are possible under some conditions (Ranjith and Rice, 2001; Ben-Zion and Huang, 2002) because of velocity weakening, heterogeneities and bimaterial contrast, and provide also one of the alternative tentative solutions to the heat flow paradox (Nielsen and Madariaga 2003). FEM calculations by Coker et al. (2005) also show generation of slip pulses for an interface with rate and state dependent frictional law.

However, these fast fronts do not explain the Rubinstein Cohen & Fineberg's slow detachment fronts which they find the most important.

We may explore therefore to return at the core of friction, i.e. at asperity level.

Recently, Rice (2006) has attempted to apply a crude Archard flash temperature 1D type approach to estimate the velocity weakening as the velocity at which asperities of size  $D$  weakens for the flash temperature having reached the critical value  $T_w$  at which the yield strength  $\tau_c$  is assumed to collapse to zero. The model is very qualitative, but when it comes to choose asperity size and their strength, he takes  $D = 5\mu m$ ,  $\tau_c = 0.1\mu$  quite high near the theoretical strength due to the assumption of the asperity size, and reasonable estimates of  $T_w$ , we have a fit to Tullis and Goldsby (2003a, 2003b) data for various rocks of interest.

Hence, it is remarkable that we have an indication that real asperity size is of the order of few microns in a quite vast range of application.

It would seem appropriate therefore to apply asperity scale models to the Schallamach waves, Chaudhurya-Kim bubbles, and slip pulses, and this means at the level of stress much higher and closer to the theoretical strength, with asperities of the size of few microns.

One interesting observation is that the size of the bubbles in Chaudhurya and Kim (2007) is of the similar magnitude as the thickness of the film which in turn is of the order of  $100\mu m$ , which here would be perhaps one order of magnitude larger than the typical size of an asperity, but still not too far.

## 4 The analogy

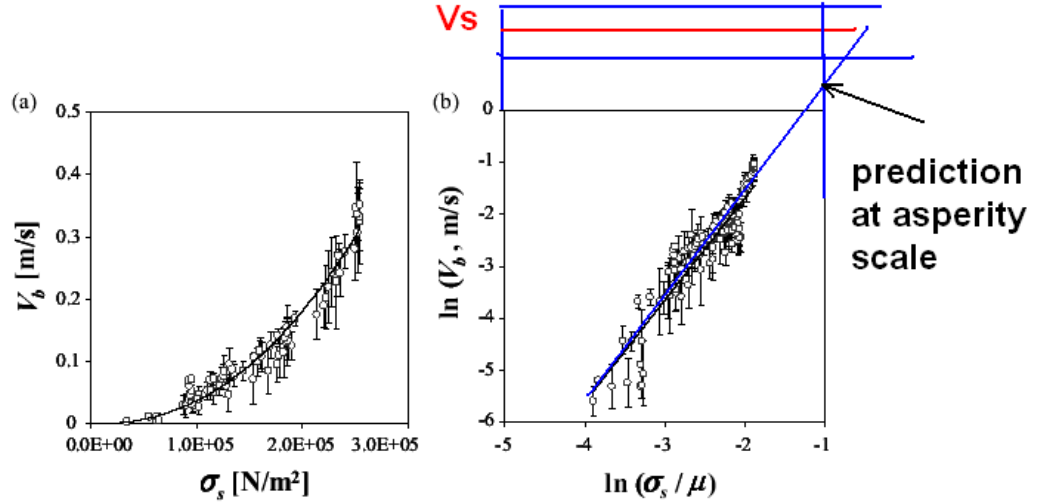
Suppose that the propagation of a bubble of Chaudhurya and Kim (2007), is analogous to the contact renewal process. CK's bubble velocity is strongly dependent on the slip velocity, and thus the applied shear stress, is not strictly a material velocity. However, CK develop an elegant approximate analysis (inspired, as it appears from the acknowledgements, by de Gennes), that accounts for the energetics of bubble propagation in a confined geometry.

Despite the dissipation in a real rubber which is estimated following a method of Shanahan and Carre, may be different from a general asperity, there is no reason to believe the basic ingredients should not be the same.

They therefore derive for the velocity of the bubble

$$V_b = V_{b0} \left( \frac{\sigma_s}{\mu} \right)^2 \quad (2)$$

where  $\sigma_s$  is the applied stress, and  $\mu$  is shear modulus. Also  $V_{b0}$  is a constant. Normally, they would find very small speeds, but extrapolating to higher levels of stress at asperity levels, indeed using Rice's estimate of near theoretical strength at  $\tau_c = 0.1\mu$ , we get a speed, which considering the  $V_s$  speed of this material (about 30m/s), is indeed 1/10 of  $V_s$ , as Rubinstein et al 2004 slow fronts. Is it pure coincidence?



**Fig. 5.** (a) The bubble velocity  $V_b$  is plotted against the shear stress  $\sigma_s$  for a PDMS elastomer of elastic modulus 1.6 MPa. The relationship between bubble velocity and shear stress is found to be:  $V_b = 2 \times 10^{-13} \sigma_s^{2.28}$  with a correlation coefficient of 0.92. (b) The bubble velocity is plotted against  $\sigma_s/\mu$  on a logarithmic scale. Here data from PDMS of various moduli (0.3, 0.4, 0.9, 1.6 and 3.2 MPa) are combined in one plot. The equation describing this plot is:  $\ln(V_b) = 1.97 \ln(\sigma_s/\mu) + 2.25$  with a correlation coefficient of 0.87.

Figure 1: Extrapolating the CK scaling velocity for bubbles to asperity size pressures, the speed of bubbles (asperity propagation) is seen to be 1 order of magnitude slower than the shear wave speed in the material.

## 5 Discussion

The Rubinstein Cohen & Fineberg's detachment fronts are a major concern for both Coulomb law (which cannot hold because it would show constant contact area), and rate-state dependent laws, which only show the fast fronts, which are seen in experiments only to justify small part of area detachment. Independently on Rubinstein Cohen & Fineberg's detachment fronts, there is a general miscomfort with the fact that if friction depends strongly on stick-slip or self healing laws, then the laws obtained by experiments could be multi-valued friction versus slip velocity curves, which even for the same material and the same experimental apparatus depend not only on the properties of the frictional interface but also on the dynamic properties of the apparatus, such as mass, stiffness and damping, so not intrinsic property of the surfaces in contact and it is unclear to what degree they can be used as a continuum constitutive law as an improvement of Coulomb's law, despite the advantage they show to regularize ill-posedness of the dynamic problem at small scales (Lykotrafitis and Rosakis, 2006).

We suggest asperity scale is playing a major role here, and is improperly taken into account when using rate-state dependent laws at macroscopic scale. It may be this simplification that makes a problem to model dynamic effects. In case the present suggestion confirms to be correct, we would still need to understand why on larger speeds of impact, the rate-state dependent laws do seem to describe correctly both the experiments and the analysis of, for example, Lykotrafitis and Rosakis (2006). The problem looks more and more complex!

## 6 References

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