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Equilibrated crater: fragmentation and mixing

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The composition of the Earth's mantle, built by impacts of metallic core planetesimals, depends on the time offered to metal–silicate equilibration (concentration equalization by mixing) as the impactor fragments settle down. Smaller fragments equilibrate while bigger ones remain segregated and accumulate in the – therefore iron rich – Earth's core. To understand the primary instability setting the interpenetration depth and wavelength between the impactor and the mantle, Lherm *et al.* (*J. Fluid Mech.*, vol. 937, 2022, A20) analyse the intermingled phenomena occurring when a drop impacts a substrate of a pool of another liquid, digging a crater. The density difference between the phases triggers a Rayleigh–Taylor instability when the drop is denser than the pool. The overall planet chemical composition relies on a tradeoff between fragmentation and mixing; this study provides elements to decipher their relative importance.

Key words: buoyancy-driven instability, drops, mixing and dispersion

1. Introduction

We have known since Newton that in order to move a massive object from rest, or slow it down to immobility, a force must be applied to it (Newton 1687, Law 1). In fluids, forces are measured by pressure gradients, and Lherm *et al.* (2022) recall that when the density and pressure gradients are in opposite directions at an interface between two fluids of different densities, then the interface is unstable. This is the Rayleigh (1883)–Taylor (1950) instability paradigm, a ubiquitous phenomenon with an immense range of applications when it comes to understanding how different phases interpenetrate, mix or fragment in non-Galilean (i.e. accelerated or decelerated) frames.

According to this principle, when a deformable object (a liquid drop) impacts a deformable substrate (a pool of another liquid), a Rayleigh–Taylor instability is likely to occur if the impacting drop is denser than the pool, a consequence of the drop/pool interface deceleration consecutive to the impact. This is actually what happens, as Lherm *et al.* (2022) have nicely shown (see figure 1*b*) by documenting and analysing step by step the many concomitant, interconnected processes at play in this phenomenon, which is simple in its principle, but turns out to be complicated (as the author's analysis is) when all the imbricated details are handled quantitatively. Elements of the phenomenology had

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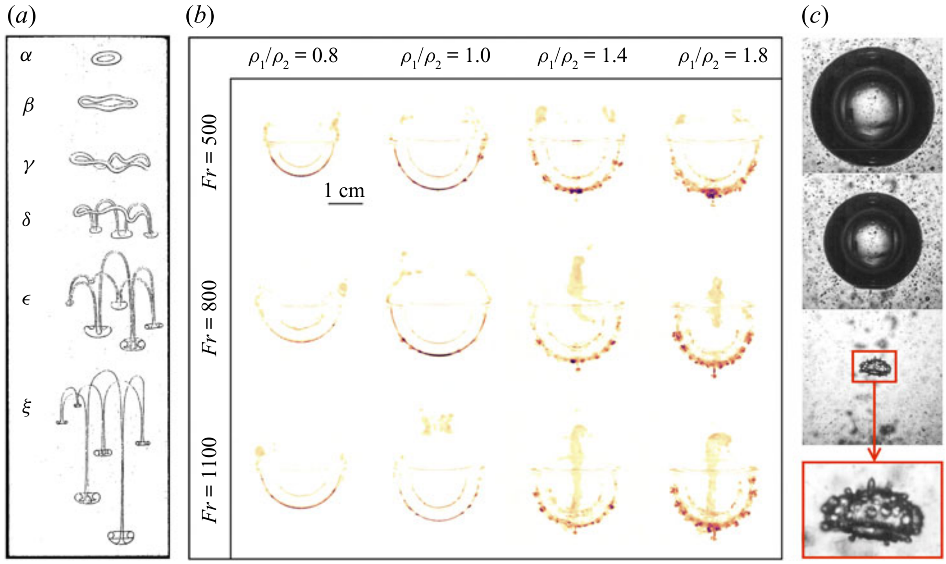

Figure 1. (*a*) A drop of heavy liquid deposited at the surface of a lighter pool forms a vortex ring which soon fragments into secondary rings; it would not do so if it were lighter than the pool, as first noticed by Thomson & Newall (1885). (*b*) Patterns of the cavity (crater) at maximal extension following the impact of a drop of density ρ_1 with radius R_0 on a pool with density ρ_2 at velocity u, defining the Froude number $Fr = u^2/gR_0$. Lherm *et al.* (2022) clearly demonstrate here that, when $\rho_1/\rho_2 < 1$, the cavity is smooth while, for $\rho_1/\rho_2 > 1$, corrugations have developed at its surface, which are more pronounced for larger ρ_1/ρ_2. (*c*) Collapse of a hydrogen–oxygen mixture ignited in a bubble immersed in a liquid, and Rayleigh–Taylor corrugations of its interface as it rebounds on the compressed burnt gases (adapted from Duplat & Villermaux 2015).

been identified long ago (Thomson & Newall 1885; Arecchi *et al.* 1996) in what the authors call the 'static' limit, when destabilization is due to permanent body forces (gravity g, see figure 1*a*).

The broad picture is that the momentum carried by the drop is absorbed by digging a cavity – a crater in the author's terminology – underneath the pool's surface, moving the fluid around in a close-to-radial fashion so that the drop crunches at the inner surface of a radially expanding, nearly spherical bubble. The expansion decelerates continuously such that if $R(t)$ is the radius of the cavity, $\dot{R} > 0$ but $\ddot{R} < 0$. This is one out of the many examples of a Rayleigh–Taylor instability in a spherical geometry, other notorious examples including the explosion of shell cases and the implosion–explosion of supernovae (Villermaux 2020, see § 5.1 for a review), or collapsing nearly empty bubbles which, at rebound when their interior has been sufficiently compressed, develop surface corrugations, a phenomenon known to compromise the efficiency of some inertial confinement fusion processes (Smalyuk et al. 2014; Duplat & Villermaux 2015, and figure 1*c*). Note that the instability in question here operates at the interface between the cavity and the pool; it should not be confused with the one affecting the border of the liquid sheet ejected from a droplet impacting a solid surface (Allen 1975), although both instabilities are of the same nature, and both occur on a decelerating, radially expanding substrate.

2. Overview

The authors interest is, however, in geophysics. Planets like the Earth were built by high-energy impacts of planetesimals with metallic cores of their own. The composition of the Earth's mantle depends critically on the time offered to metal–silicate chemical equilibration (meaning concentration equalization through mixing) as the impactor material settles towards the Earth's core. Efficient equilibration is achieved with smaller fragments, allowing fast metal–silicate mass transfer, while the fate of bigger ones is to accumulate in the – therefore iron rich – core (Deguen, Landeau & Olson 2014; Landeau, Deguen & Olson 2014). The overall planets chemical composition thus relies on the initial fragmentation state of the crunched impactors since this initial division state will determine in all cases the subsequent molecular mixing kinetics of the fragments in the molten silicate magma. This is the reason why documenting primary instabilities, such as the typical wavelength of the contacting Rayleigh–Taylor instability, which sets the length scale at which the impactor and the mantle interpenetrate, and the net depth of interpenetration, is paramount.

Through delicate but precise enough experiments in the spirit of those of the early contributors to the field (Lewis 1950; Emmons, Chang & Watson 1960; Niederhaus & Jacobs 2003), the authors embark on this endeavour. Admittedly, this is not an easy task since, in this problem, the instability is caused by a time varying deceleration ($\ddot{R} < 0$ decays in time but not fast enough to be considered as impulsional) on a expanding substrate ($\dot{R} > 0$) and applies to a fluid layer (the crunched drop pancake covering the cavity) which itself gets thinner in time. The impacting drop inertia triggers the pool motion, which is counterbalanced by buoyancy because gravity tends to level out the cavity. With the help of fudge factors introduced to compensate for the lack of energy conservation in the formulation, which is basically conservative in a close-to-spherical but not exactly spherical geometry, the authors nevertheless make sense of the cavity dynamics, and derive from it a fair caricature of the crunched drop layer destabilization; its wavelength is controlled by inertia, buoyancy and the viscosity of the pool, a result which was not obvious from the start.

The only ingredient the authors neglect is capillarity. Considering the application they have in mind, namely the formation of a crater by the impact of an asteroid falling on Earth (for which the Weber number is astronomical), this neglect is legitimate; but in view of their much more gentle experimental conditions, the non-importance of surface tension is less obvious. There is a special limit of the Rayleigh–Taylor instability for thin layers (as opposed to an interface separating two semi-infinite phases) when surface tension operates (Keller & Kolodner 1954; Bremond & Villermaux 2005). Here, a dense decelerated layer is sandwiched between two lighter phases (the pool and air). We know that the proximity of the two interfaces on each side of the layer not only affects the growth rate, but also the instability mode selection, both being a function of the layer thickness. The authors disregard this effect because the preferred wavelength in their experiments is of the order of, or smaller than, and in any case independent of it. But this effect does exist, and has been shown to fully operate in systems very close to theirs, in a true spherical geometry (Vledouts *et al.* 2016).

3. Future

The study of Lherm *et al.* (2022) culminates with an estimate of the pool material mass entrained through the instability development. It can be ten times as large as the impacting drop mass; this provides a measure of the dilution level the metal/silicate mixture will have once molecular mixing (equilibration) is achieved. This entrainment index is the equivalent of the 'mixing layer thickness' in shear flows; it gives an idea of the extent of the inter-dispersion region between the phases, but says nothing about their fine-scale interpenetration at the molecular scale, which is mixing *per se*. The phases could well remain segregated from each other, however, chemically equilibrated implies molecularly mixed. The authors are well aware of the distinction between stirring and mixing (Villermaux 2019) and know, in some prototypical situations, how to articulate one with the other (Lherm & Deguen 2018). This important aspect remains to be quantified in the present configuration, a goal which should be attainable given the quality of their diagnostics.

Also, knowing the instability length scale in the interpenetrated region between the phases is useful because it sets the typical stirring scale for describing the mixing kinetics further, but we also know that fragmentation phenomena give rise to broad distributions of fragments sizes (Lhuissier *et al.* 2013, although capillary aggregation certainly plays a role there). Identifying the proper instability at play, and the emergence of its preferred length scale is one good thing, but describing the fragmentation process in its diversity and the nature of the induced, competing mixing of the fragments assembly is another level, certainly on the author's agenda for the future.

Declaration of interests. The author reports no conflict of interest.

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