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Fall and fragmentation of liquid metal in a viscous fluid

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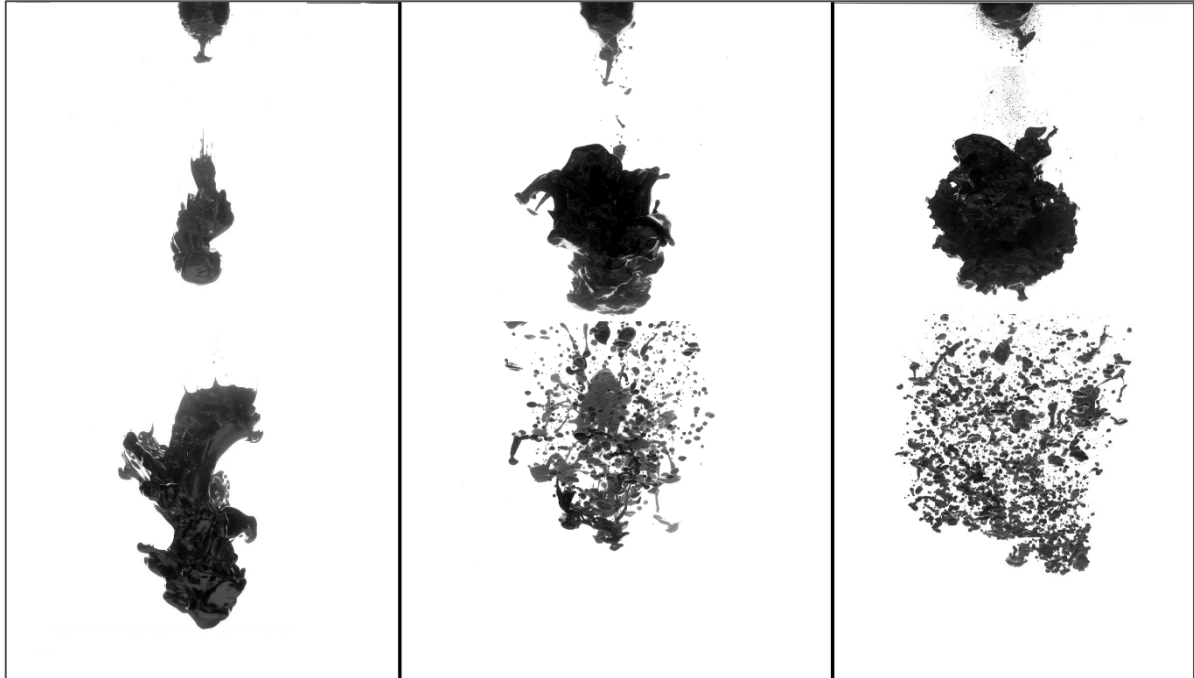


Figure 1: Superimposition of three snapshots extracted at the same time (time interval of xxx s) from 3 videos of the fall of a mass of liquid metal with an initial 31 mm spherical radius in an ambient fluid with different viscosities. From left to right the viscosity of the ambient fluid decreases by 3 orders of magnitude. The corresponding viscosity ratio between the two fluids are 700, 80 and 0.4, and the corresponding Reynolds numbers are 20, 195 and 34000. The Weber number is 51 in all cases. See also the video at <https://doi.org/10.1103/APS.DFD.2016.GFM.V0038>

Simulations of the solar system formation as well as the diversity of meteorites chemical composition both point toward a scenario where the late stages of Earth-like planets accretion involved massive impacts of Mars size planets [1]. Due to the combination of the energy release during impact, to the intense radioactive decay of short-lived elements, and to the heat remaining from the conversion of potential energy required to form a planet, these planetary embryos were most likely molten for a large part [2]. This also means that they were differentiated in a liquid iron core covered by a molten silicate mantle, since these two main phases of terrestrial bodies are immiscible and of significantly different densities. Following each impact, a large-scale two-phase flow occurred as the molten iron of the impactor core flowed across the silicate magma ocean to merge with the planetary embryo core. Because of the immense inertia of the process, this flow was characterized by very high Reynolds and Weber numbers, hence prone to rapid fragmentation. The quantification of the exchanges of heat and elements in this dispersed flow is crucial to the knowledge of the initial state of telluric planets.

While the dynamics of rising bubbles have been largely investigated [3], studies of the planetary regime of two-phase flow and fragmentation are sparse. Models of Earth's formation mostly rely on asymptotic models where the initial volume of iron is either immediately spread into an ensemble of

drops of capillary sizes that behave independently [4], or remains as a whole until reaching the bottom of the magma ocean, developing Rayleigh-Taylor and Kelvin-Helmholtz type instabilities on its sides [5]. Recently [6, 7] performed laboratory experiments showing that in the relevant large Weber number limit, the released buoyant fluid behaves initially like a turbulent thermal whose surface of contact with the ambient fluid has a fractal aspect and therefore a large surface area, well before fragmentation and formation of a cloud of droplets.

The viscosity of the magma ocean is a key variable in the geophysical application. We have thus constructed an experimental set-up using Galinstan, a metal liquid at room temperature, to mimic the impactor core, and a mixture of water and industrial lubricant (Ucon Oil) with a tunable viscosity, to mimic the magma ocean. A given volume of Galinstan is initially placed at the top of a 1m deep tank inside a balloon, which is suddenly popped. The following dynamics is recorded using a high-speed camera. As shown in fig. 1, changing the viscosity of the ambient fluid by a factor of 1000 does not change the mean falling speed significantly, which is in reasonable agreement with the inviscid scaling for the terminal velocity of the initial spherical mass of metal. Nevertheless, the viscosity ratio has a great influence on the fragmentation regime. At low viscosity ratio (fig.1 center and right), the liquid metal is rolled in a turbulent vortex ring and stretched until the thin liquid metal sheet breaks-up in a single event, in qualitative agreement with the fragmentation mode found by [6]. At the higher viscosity ratio (fig. 1 left), vorticity tends to be localized in the liquid metal; it is not rolled-up but stretched in long scales so that breakup rarely happen in a single event. Instead the liquid metal is peeled away from the initial mass or separates from the rest via Rayleigh-Taylor instabilities.

When increasing the inertia of the flow, one could expect a dynamic similar to the immiscible case, corresponding to a turbulent thermal [8]. While the linear increase with depth of the mean radius of the metal blob agrees with the classical theory for turbulent thermals, this model systematically overestimates our measured velocities. We conjecture that this is due to the invalidity of the turbulent entrainment hypothesis, where the buoyant mass entrains fluid all along its surface with no significant initial momentum [9]. As shown in fig. 2, we observe that the ambient fluid is engulfed at the rear of the liquid metal only, where strong stable vortices produce important velocity gradients in the ambient fluid. This flux produces an expansion of the liquid metal sheet that works against surface tension, producing an over-pressure in the entrained liquid that could accelerate the falling velocity. The validation of this explanation now requires precise velocimetry in the ambient fluid that will be the focus of our next studies.

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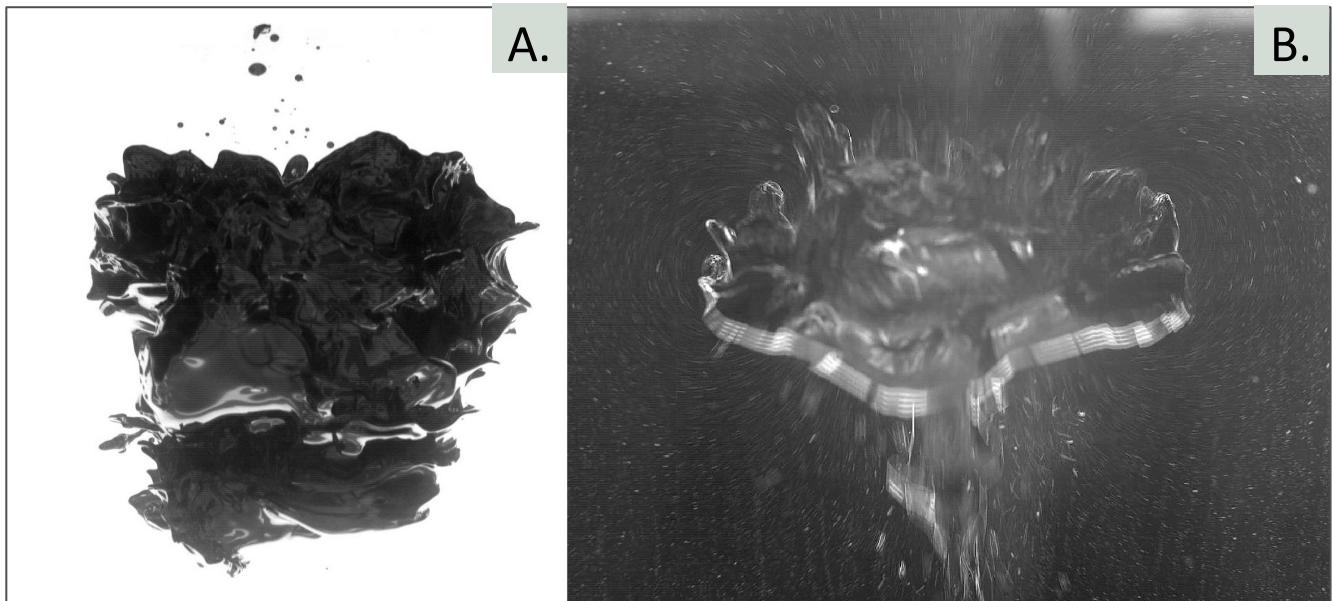


Figure 2: Picture of the fall of a 31 mm in radius initial mass of liquid metal illuminated (A) from behind by a LED plane and (B) from the side by a ring light, with the ambient fluid previously seeded by a vertical plane of gas bubbles. The corresponding viscosity ratio is 8, the Reynolds number is 1700 and the Weber number is 51. See also the video at <https://doi.org/10.1103/APS.DFD.2016.GFM.V0038>

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