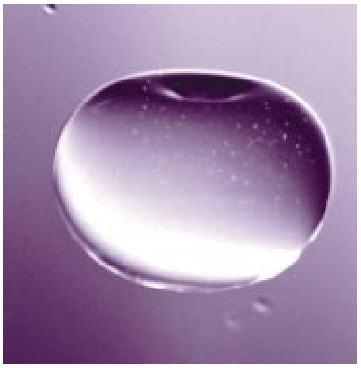

FIG. 1. 0.5 ml.

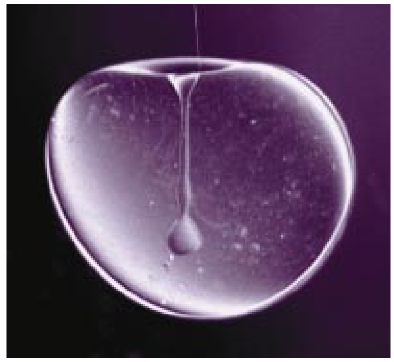

FIG. 2. 1.4 ml.

FIG. 3. 3.8 ml.

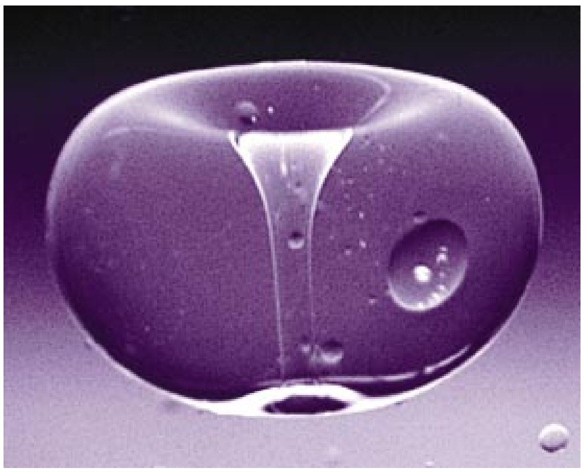

FIG. 4. 6.2 ml.

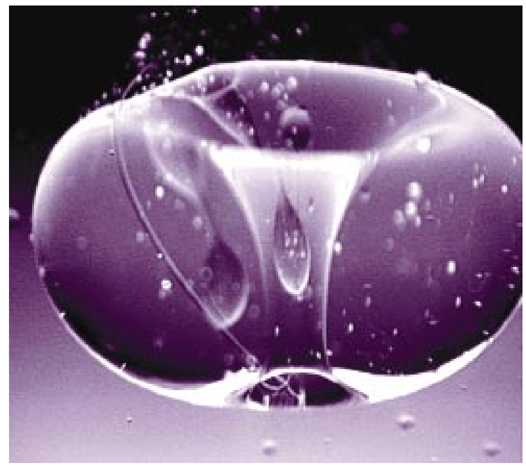

FIG. 5. 17 ml.

Dynamics inside Polymer Drops: From Dimple to Rayleigh Instability to Torus

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The free boundary shape of a rising bubble or falling drop is a sensitive measure of the balance of the interior and exterior fluid forces. When the drop phase is a dilute polymer solution, a number of new instabilities occur.[1] Our experiments involve an aqueous solution of 0.2% Xanthan gum (polymer) in 80:20 glycerol/water falling through PDMS oil (viscosity of 10 Stokes). The polymer drop is introduced at the top of an oil-filled column as a roughly spherical globule, and its steady state shape is observed from 30–60 cm down the column. Typically, the drops can have Reynolds numbers up to 2, and Deborah numbers up to 4. At a volume of 0.01 ml, the drop is spherical, while for volumes from 0.05–0.24 ml, the drop has an oblate spheroidal shape. Above a critical volume of 0.25 ml, a dimple is observed at the rear of the drop (Fig. 1). It is well known that a transition to dimpled drops occurs due to inertial effects. However, the deformation we observe is not due to inertia, confirmed by the spherical shape of the same drop without the polymer. As the volume of the drop is increased further, the dimple becomes unstable, and is pulled down into the drop (Fig. 2). This has the appearance of the classic Rayleigh instability for a filament pulled by a pendant drop. What is unusual here is that the pendant oil drop is *lighter* than the surrounding polymer fluid.

For even larger volumes, the filament of oil becomes wider and more stable, extending down to the leading edge (Fig. 3) where it eventually coalesces with the front surface, making a toroidal drop (Fig. 4). This process often results in the pinchoff of the pendant oil drop, which is pushed off to the side. Polymer drops in excess of 10 ml can display very complex behavior, including ejected drops and multiply wrapped filaments (Fig. 5). Although toroidal drops have been seen experimentally in Newtonian fluids, with one exception[2] it has always been for two miscible fluids.[3] In the experiments of Baumann *et al.*,[2] surface tension forces were small and the torus ''rapidly expanded'' and broke apart. In our experiments the torus is produced by the elasticity of the polymer solution in spite of surface tension, and is stable.

[1] M. C. Sostarecz and A. Belmonte, ''Motion and shape of a viscoelastic drop falling through a viscous fluid,'' J. Fluid Mech. (to be published).
[2] N. Baumann, D. D. Joseph, P. Mohr, and Y. Renardy, ''Vortex rings of one fluid in another in free fall,'' Phys. Fluids A **4**, 567 (1992).
[3] For example, see M. Kojima, E. J. Hinch, and A. Acrivos, ''The formation and expansion of a toroidal drop moving in a viscous fluid,'' Phys. Fluids **27**, 19 (1984).