Surface Tension*

By DR. ALLAN FERGUSON

OUR subject is very closely associated with the comprehensive topic of cohesion, a topic which attempts an answer—not to the problem, *why* we are here to-night, which is a matter for the theologians to discuss—but the problem, *how* we are here, in our present habits, and not as a chance medley of unattracting atoms. To attempt to answer such a query takes us very far towards the fundamentals of atomic structure and behaviour, but the problem, as we envisage it in the light of to-day's theories, still bears a strong resemblance to the problem as it was posed, and answered, by van der Waals. How comes it that, if material particles attract each other, the whole structure of the universe does not collapse under these attractions? We can formulate an answer to the question if we take into account the thermal motions of the particles. "In nature it is cohesion between atoms which tends to produce condensation and solidification, and temperature which tends to produce dissociation. . . . Temperature is a manifestation of kinetic energy and cohesion of potential energy and the interplay of these two forms of energy is responsible for many of the observed physical properties of matter" (Lennard-Jones). Cohesion and temperature—these, then, are the protagonists who play out the drama.

The main change of view during the last generation depends on the change which has taken place in our concept of the ultimate material particle and the structure of the atom. The billiard ball atom of the nineteenth century physicist served its purpose well, and subserves a useful function to-day. It is not surprising that so naive an extrapolation of our large scale processes should ultimately break down—the surprising matter is that the extrapolation should have proved so brilliantly successful as it has done. Such a type of atom was assumed to have a definite size, and this notion of clear-cut dimensions was not lost when it was found that the concept was not fine-grained enough to interpret successfully radioactive phenomena, and the nuclear atom displaced it. Here the concept of size was associated with the dimensions of the electronic orbits and, though the atom became a far more complex system, there was no haziness about the notion, apart from the difficulty of an exact determination of its dimensions.

We have changed all that to-day. We cannot hope to locate our electrons precisely and the definite orbit of the electron of the nuclear atom is now replaced by a *probability pattern*, the density of the pattern at any point measuring the probability of finding an electron there. Fortunately, the uncertainty which we have introduced into our concepts has not seriously altered our views concerning the order of atomic magnitudes, inasmuch as the probability of finding

an electron in any particular pattern becomes infinitesimal outside regions of the magnitude of about one hundred millionth of a centimetre. We may still, therefore, keep to an interpretation of the size of an atom which, despite a little cloudiness at the edges, does not differ materially from the interpretation based on the older concepts.

What are, then, the dimensions of the atoms and molecules with which we have to deal? Any example that we may give to illustrate the meaning of such atomic magnitudes merely transforms an inconceivably small number into an inconceivably large one; let it suffice to say that if we could curb the liveliness of the hydrogen atoms and lay them in order on a sixpence, it would take some eight hundred million years of unceasing work to cover the coin, if we laid our atomic bricks at the rate of one a second.

We shall, therefore, picture a liquid as a congeries of such particles in lively thermal motion, attracting and being attracted according to a law which we need not attempt to specify more closely than by saying that the attraction of any one molecule on its neighbours falls off very rapidly as the distance increases. If then we draw round any one molecule, well in the interior of the liquid, a small sphere the radius of which we may term the range of molecular attraction, the central molecule will experience no resultant force due to the attractions upon it of its neighbours within this sphere.

It is otherwise if the central molecule is at a distance from the surface of the liquid which is less than the radius of this sphere. Part of the sphere is now outside the liquid, the molecules therein are missing, and do not contribute their share to the force on the molecule at the centre of the sphere, which molecule therefore experiences a force urging it into the liquid. To transport a molecule from the interior of the liquid into the liquid surface against such a force requires, therefore, the expenditure of *work*; and inasmuch as the conveyance of molecules into the surface means an extension of the surface, to extend a liquid surface necessitates the expenditure of work. Stretch a sheet of rubber, and notice that we have to do work to extend the rubber surface.

We must not press simple analogies too far, but it is legitimate to assume that the surface of a liquid behaves as if it were in a state of tension, and the tension in the surface across a line of unit length drawn in the surface is called the *surface tension* of the liquid. We may demonstrate its existence by forming a soap film on a circle of copper across which a loose thread of cotton has been tied. Destroy the film on one side of the thread, and the thread is pulled by the tension of the film on the other side into a very perfect arc of a circle. This tension differs for different substances,

* From a Friday evening discourse delivered at the Royal Institution on February 16.

as we may show by pouring a little alcohol on to a thin film of coloured water at the bottom of a glass dish, and noting how a clear space is formed in the middle of the dish where the alcohol—the liquid of weaker tension—was poured in.

For any one liquid, the tension decreases with increasing temperature. We may show this by scattering lycopodium on the surface of water in a dish, and bringing a heated bit over the centre of the dish. The greater tension of the cold water is clearly shown by the way in which the central space is swept clear of the powder. Following Lord Kelvin's dictum that we know something about a quantity when we can make measurements thereon, it may not be amiss to state that the law connecting surface tension (γ) with temperature (θ) is $\gamma = \gamma_0(1 - b\theta)^n$, where b is very accurately the reciprocal of the critical temperature, and n , which varies only slightly from liquid to liquid, may be assumed to have a mean value of 1.2. This relation holds good for *unassociated* liquids. A film of oil covering a thin rod breaks up into a series of regularly spaced drops, illustrating the instability of a liquid cylinder the length of which exceeds its circumference. A similar result may be illustrated for a liquid annulus by cutting a narrow circular groove on the lower surface of an iron disk, placing the disk on a horizontal glass plate and filling the groove with mercury. On lifting the disk, the ring of mercury breaks up at once into a series of regularly spaced drops.

These drops take on an approximately spherical form, and the tendency to sphericity becomes more pronounced as the drops become smaller, and those forces, such as the weight of the drop, become increasingly unimportant in comparison with the surface forces. A spherical surface is that surface which, for a given volume, has a minimum area, and this tendency to the exposure of the smallest possible extent of surface illustrates the principle that a dynamical system tends to take up a position in which its potential energy is a minimum.

Another experiment we owe to the ingenuity of Major C. E. S. Phillips. Two light vertical rods serve as supports. To the top of one is fixed a *circular* microscope cover slip with its plane horizontal; the other support carries a horizontal *square* cover slip. Two other slips, one square, one circular, carry fastened to their upper surfaces long and light straw pointers. Lay these on the top of the fixed slips, and, clearly, you can spin them round as you will. But now place a drop of water between each of the pairs of slips, and endeavour to revolve the upper movable slips. The circular one moves freely over its circular fellow and remains with its pointer pointing in any direction which you choose to give to it. Displace the square one, and it snaps back into a perfectly definite position of equilibrium in which the upper slip is exactly congruent with the lower. It is a delightful experiment, and one is tempted to say of it, *mutatis mutandis*, what Praed said of the Vicar's sermons.

These few fundamental principles, consistently applied, will serve to elucidate a great many problems in which surface energy plays a dominant part.

But we must hasten to the second part of the discourse, which is concerned with a very commonplace phenomenon—that of the detachment of a drop of liquid from a vertical tube. Study the process at any slowly dripping tap, and you will see that, although the initial stages may very easily be examined, the final stages of detachment occur with a rapidity which makes it impossible for the eye to follow them. How may we slow the process? Aniline and water are almost immiscible, and the density of aniline is but slightly greater than that of water. If, therefore, we form an aniline drop at the end of a vertical tube dipping into water, we may project the image of the drop on to a screen, and study the circumstances of its detachment with much greater ease.

Pitch is a queer substance: to forces of short duration it behaves as a solid; leave it to itself, and it will flow like a liquid. Pitch in a funnel gives a very perfect drop of pitch pendent from the stem of the funnel. It seems static enough; but although it flows, like Caesar's Arar, *incredibili lenitate*, nevertheless it *does* flow, as a few months' inspection would show.

Yet another way in which we can slow down the process. A sheet of indiarubber is stretched, tambourine fashion, across a circular frame, and held in position by a serving of cord and a tourniquet. If water is slowly run into the tambourine, the rubber first assumes a lenticular form and then takes on a position of equilibrium in which a pronounced waist is seen in the profile of the drop. This position, impossible as an equilibrium position in a water drop, is possible here because the tension in a rubber surface increases with the extension, whereas the tension in a liquid surface is, under conditions of constant temperature, independent of the extent of the surface. This experiment was shown by Lord Kelvin at the Royal Institution in his Friday evening discourse of January 29, 1886. If his biographer ("Life of Lord Kelvin", p. 854, vol. 2) is a veracious chronicler the growth of the drop "furnished an exciting episode in the lecture, which culminated when finally the elastic film gave way and the drop burst over the lecture table, splashing the nearer members of the fashionably attired audience".

Even in 1886, it was possible to take an instantaneous photograph of the detachment of a drop of ink from a funnel; to-day the progress of high-speed cinematography has made it possible to follow the details of the process with the camera. A high-speed camera, developed in the Bell Telephone Laboratories in conjunction with the Eastman Kodak Company, makes it possible to take photographs at a normal rate of a thousand per second and, by overvolting the motor, we have been able to increase this rate to nearly two

thousand per second. Obviously at these speeds the intermittent jerking of the film through the camera is impossible, and the film hurtles past the lens at a uniform speed of close on thirty miles an hour when the motor is overvoltage. Between the lens system and the vertically descending film is a prism which can be rotated about a horizontal axis at a maximum speed of eighty thousand revolutions per minute, and this prism permits twice in each revolution of the passage of light from lens to film, and therefore exposes an image on the film for a period of the order of one five-thousandth of a second. There is no special difficulty in the illumination of the object; in all the experiments to be described a thousand watt lamp and a simple projector gave all the illumination necessary. A special feature of the camera is a two-dialled clock; one of the dials rotates once a minute and registers seconds; the other dial rotates once in a second and is graduated into five hundred divisions in such a way that thousandths of a second may be estimated. An auxiliary prism throws the images of these dials on the film, and the time relations of the phenomenon under observation may therefore be registered with very high accuracy.

Readers of the fantasies of Mr. H. G. Wells will remember that delightful story in which the hero takes a drug which temporarily alters his time-scale of living. Under its influence he writes a three-hour article at what he presumes is his normal rate; when the effect of the drug has worn off he finds that he has accomplished his task in a few minutes. He takes a walk, and notices a bee flapping its wings lazily in the wind; he accelerates his speed, and is brought up by a smell of burning—the rapidity of his motion through the air has caused his trousers to singe.

Suppose, then, we make an attempt to enter a world the time scale of which is such that we can study the manner in which a drop detaches itself from a tap—we can do this by running a film taken by the high-speed camera through the projector at a rate of fifteen or twenty pictures a second. We have altered our time scale in the ratio of about a hundred to one. In this way (Fig. 1, B) all the stages of the detachment of a drop, and the lenticular form, the waist formation, the drawing-out of a long neck and the final detachment of the drop and its accompanying satellite can be followed with the greatest ease.

But the most interesting application of cinematography of this type which I have as yet

been able to make, is the study of the beautiful phenomena described some thirty or forty years ago by Prof. A. M. Worthington, who photographed the splash of a drop of liquid into liquid, of a solid sphere into a liquid, and of a liquid drop falling on to a solid plate ("A Study of Splashes", 1908). That something odd happens

FIG. 1.

when, *ex. gr.*, a drop of water falls on a smoked glass plate is well seen on these slides, the radial striations on which show that the drop has been throwing out arms in what, at first sight, seems a very queer fashion.

Worthington investigated the phenomenon by taking an instantaneous photograph of, say, a

drop of water falling into milk at a certain stage of its fall and then, by an ingenious timing device, ensured that a second drop, released under conditions identical with those of the first drop, should be illuminated instantaneously at a stage of its fall one five-hundredth of a second later than that stage at which its predecessor was illuminated; and so on. Worthington, in fact, took photographs of different drops at varying stages of their careers and from the photographs pieced together the life-history of a single drop. The high-speed camera enables us to do this directly, and frees us from certain obvious complexities introduced by the varying behaviour of different drops—complexities which, on occasion, proved very puzzling to Worthington.

The film (Fig. 1, A) which shows the splash of a water drop into water is not perhaps so spectacular as some of the others, but it has a mild historical interest inasmuch as it is, I think, the first film to show the phenomenon, and it was actually our first film, taken with no special precautions as regards stopping of the lens and illumination. Addition of a little milk to the water brings out

the detail, and it is most interesting to note how closely the story follows that unfolded by Worthington's pictures. We see the effect of a low fall, about 40 centimetres (Fig. 1, c) and of a high fall, about a metre (Fig. 1, d), the high fall showing very beautifully the stages in the process of bubble formation on the surface of the liquid. In Fig. 1, E and F, are shown the effects of a low and of a high fall due to an ordinary rough marble sphere falling into a liquid. The whole story of these events is told in something of the order of half a second, and the slow motion projection enables us to multiply this period by a factor of about a hundred.

The splash of a drop of mercury on a glass plate is a little more difficult to follow—it is over in about a twentieth of a second, and even the high-speed camera is not quick enough to enable us to grasp the complete detail. Nevertheless, we hope to be able to speed up the camera still further, and this gain of speed, with the aid of the technique of the photographer, may make it possible to show to an audience even so evanescent a phenomenon as this.

Germination of Seeds*

By SIR ARTHUR W. HILL, K.C.M.G., F.R.S.

WE may now consider those seeds which on germination escape from their endocarps or stones by throwing off a specially-prepared portion only of the endocarp wall. The best examples of such fruits, enclosing a single seed, are afforded by the tupelos, *Nyssa*, and by *Mastixia*, both belonging to the family Cornaceæ. The valve, which is thrown off on germination; which may be compared to the shutter of a shop front, is about one-third the length of the stone, square-cut at the base, with a bluntly triangular apex. Until germination commences it is scarcely possible to see the outline of the valve, since the surface markings of the stone are continuous over the valve and the rest of the fruit. When germination commences and the substance cementing the valve to the rest of the endocarp is dissolved, the radicle pushes off the shutter, which becomes completely detached, and so the embryo effects its escape. It is of interest to notice that specimens of fossil seeds of *Nyssa* and *Mastixia*, found in Eocene beds in the Isle of Wight and in Pliocene beds of the Dutch-Prussian frontier, show the valve structure perfectly. There is a further interest in these fossil seeds, since *Nyssa* to-day is only known in the eastern United States, the Himalayas and the Malayan Islands, and *Mastixia* in India and the East Indies.

The cornels, *Cornus*, have fruits of a similar character, but differ in having two seeds enclosed in an endocarp, which necessitates the splitting off of two shutters, one for each embryo, when

germination commences. As in *Nyssa*, the shutter has a horizontal base, and before germination takes place the presence of the valves or shutters cannot be detected.

The fruit of *Canarium* (Burseraceæ) contains three seeds enclosed in a stony endocarp. The hard woody valves or shutters are triangular-ovate, pointed at the apex and horizontal at the base, and are about two-thirds the length of the stone. On the inside they are concave. The seed cavity is the full length of the stone and the radicle of the embryo is at its broader upper end. On germination, the radicle pushes the shutter upwards and the arch of the hypocotyl raises the shutter still more. The embryo, however, is well surrounded by its seed-coats and in order to extract its cotyledons properly a peg-like structure is developed at the apex of the radicle on the seed side, which grows over the lower edge of the stone much as in the vegetable marrow. The young seedling thus treads on the floor of its prison box, keeping it firmly on the soil, while the hypocotyl, exerting its full pressure, withdraws the cotyledons both from their own seed-coats and from their wooden, box-like prison.

The seeds of the teak tree (*Tectona grandis*, Verbenaceæ) show a similar arrangement of shutters. Here, however, there are four cavities in the endocarp and the four shutters extend nearly the whole length of the stone. When the shutters are thrown off on germination the destruction of the prison has been so complete that only the partition walls remain. *Saccoglottis*

* Continued from p. 859.