The Formation of

Rotating Rings

(Vortex Rings)

of

Air and Liquids

Under Certain Conditions of Discharge

By

Prof. William B. Rogers

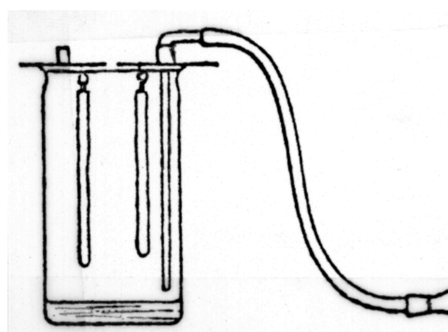
New Haven
Printed By E. Hayes
1858

ON ROTATING RINGS
OF
AIR AND LIQUIDS

It has long been a familiar fact that the bubbles of phosphuretted hydrogen gas consisting of PH_3 with an admixture of PH_2, give rise by their explosive combustion in the air to a ring of white vapor-like phosphoric acid, which dilating as it ascends exhibits a rotation of each vertical element around the curved axis of the figure. A similar motion is sometimes discernible in the smoke from a cannon, and in the steam which escapes by momentary puffs from a steam-pipe, and as expert smokers know, such revolving rings are readily produced by ejecting the smoky breath in a peculiar manner from the rounded opening of the lips.

In studying recently the phenomena of air-jets, I have been led to a somewhat critical examination of the conditions under which these ring-discharges are produced. By the use of suitable arrangements I have been able not only to trace the development of the rings produced in air projected from apertures, but to detect similar movements in that which is released by the bursting of an ordinary bubble. I have, moreover, by a modified contrivance succeeded in forming at will similarly constituted rings from water and other liquids, and in tracing them to the same mechanical causes which give origin to the rings of air. As the methods of experimenting which I have adopted, as well as most of the observations, appear to be new, and as the mechanism of these beautiful effects has not, that I am aware, been specially treated of before, I trust that the following details may be regarded as a not uninteresting addition to our knowledge in this department of inquiry.

I. *Of the air-rings formed by momentary discharges from an aperture.*


1.

1. *Mode of producing the air-rings*.- To render the form and internal movements of the escaping air in such cases distinctly visible, I use a large glass reservoir, (fig. 1) in which the air is kept opaque by a continual supply of chloride of ammonium generated within. To the top of the jar is adapted, by grinding and an unctuous cement, a zinc or glass cover pierced with three holes, *viz.*: a central round aperture one inch in diameter, and two others of much smaller size, each furnished with a short socket-tube rising above the plate. Of these, one is intended for connecting with tubes of discharge, and is kept closed when the central orifice is in use. The other receives a slender glass tube, entering above by a rectangular bend and descending to within two inches of the bottom of the jar. At its outer end this is connected with a flexible pipe through which the operator, impelling the air in successive puffs into the lower part of the vessel, can at will eject corresponding volumes of the cloudy air through either of the apertures. For this purpose he may either use the mouth, or a gum-elastic bag attached to the end of the tube - the former being in most cases the preferable instrument. At equal distances on opposite sides of the central hole, two hooks are affixed to the lower surface of the plate, from which are suspended long slips of thick cotton cloth.

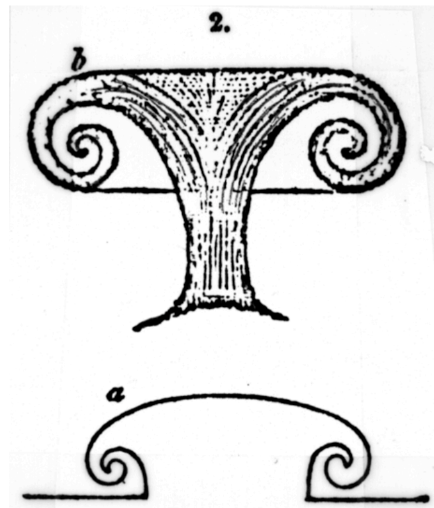
To prepare the apparatus for experiment, we remove the cover and pour into the jar common hydrochloric acid to the depth of half an inch, adding to it one or two cubic inches of nitric acid.

The slips of cotton cloth, after being dipped in strong water of ammonia, are replaced on the hooks, and the cover restored to its position with a slight pressure to render the junction firm and air-tight.

The included air quickly becomes opaque with the dense cloud of chloride, and by applying the lips to the free end of the flexible tube may be expelled from the aperture which is left unclosed, either in the form of successive puffs or of a continuous jet. It is almost needless to say that in making the experiment the surrounding air should be as little moved as possible, the slightest agitation near the aperture sufficing to mar the symmetry of the effect.

2. *Stages of the ring-formation.*- When by a moderately strong impulse the cloudy air of the jar is to issue in a succession of quick but not violent puffs, each little cloud assumes near the aperture the form of a ring, which gradually dilating as it rises retains its symmetry until it has reached the height of two or sometimes even of three feet above the opening.

Using a gentler and less sudden impulse we cause the ring as it ascends to carry with it a train of cloudy air *which forms the downward continuation of the inner portion of the coil.*



With a still lighter breathing at the mouthpiece we may expel the air in so gentle a wave as to be able to mark the escaping cloud rolling slowly over on each side of the aperture without breaking its connection with the central mass - the whole thus assuming the appearance of the top of a column adorned with volutes. In these experiment no actual ring is generated, but we have the opportunity of watching the beginning of such a form and tracing the mechanical movements to which it owes its development. In fig. 2 the earliest stage is indicated by *a*, and the imperfectly formed ring with part of the attached train by *b*, the lateral sections of the ring only being represented.

When the discharge is produced by a stronger impulse than in the case first mentioned, the resulting ring darts upward so rapidly as to break away from its train, leaving the latter either to lag behind as a formless mass, or, when retaining sufficient velocity, to evolve from its own substance a second and smaller ring which is seen quickly pursuing the first. By applying a yet more energetic force, we may cause the ejected air to form three, four, or even a greater number of such successively developed rings.

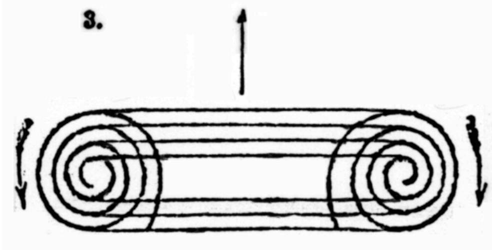
The size of the ring when first formed is dependent chiefly on the width of the aperture, and in some degree also on the strength of the blast. With a hole one and a half inch in diameter, and a proportionally large injecting tube, it is easy, by a suitable impulse of the breath, to generate rings of from two to three inches in diameter of the most perfect symmetry, and having force enough to ascend unbroken to a height of six or eight feet. In this way we may render these beautiful phenomena visible over a large apartment, causing the smoky wreaths to chase each other until flattened against the ceiling.

If instead of the mouth we use the elastic bag as a means of impelling the cloudy air, we find that a quick pressure and subsequent withdrawal of the hand give rise to rings of great symmetry, and that these are usually unaccompanied by any train. The latter result is evidently due to the sudden recoil of the bag, and the consequent retraction of the latter part of the cloudy mass back into the reservoir. By continuing the pressure so as to prevent the recoil we may produce the same phases of the phenomena as when the impulse is given by the breath.

3. *Rotation and structure of the air-rings.*- To obtain a distinct view of the motion and internal structure of the ring, it should be viewed in a nearly horizontal direction, and by a strong

transmitted light. This is conveniently done by placing the apparatus on a table a little below the level of a gas lamp, but at a considerable distance from it. It will then be seen that the rotation of the ring, either in its incipient stage, or with the attached train, or when entire and separate, has always one direction, the inner circumference being carried forward or in the ordinary mode of experiment upward, and the outer in the reverse direction, as shown in fig. 3. In order that the eye may readily follow this motion in the interior of the ring while it retains its perfect form and rapid rotation, the air of the reservoir should be only moderately cloudy, and the impelling force quick without being violent.

3.



Under these circumstances we observe *the ring to be made up of a coil of cloudy air - between the folds of which is rolled up a similar coil of transparent atmosphere.*

When the ring carries a train it is easy to discern that the cloudy spiral is continuous with this attendant mass, and really issues from it near the inner circumference of the ring. In a yet earlier stage of the action we are able to mark the beginning of this two-fold spiral by observing how each volute as it draws its supply from the central mass gathers in a portion of the clear external air to be enfolded between its turns.

4. *Origin of the rotation.-* This is obviously preferable to the combined agency of the outward impulse and the resistance which the sides of the issuing mass encounter from the edge of the opening, and from the air into which it is impelled. The former of these forces, due to the tension propagated through the reservoir, must to some extent operate in diverging directions, while the resistance acts in nearly opposite lines. Thus, at the outset, there would be produced a reversion or curling of the issuing cloud around the aperture, which, as the action continued, would be developed into the spreading volutes before described, and at length into the perfect and rapidly revolving ring.

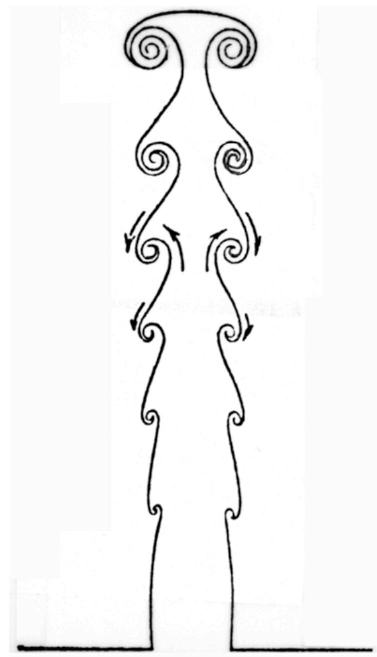
The dilation of the ring in its ascent would seem to be the natural result of the divergent character of the impulse impressed upon the air as it passes from the orifice.

5. *Horizontal bands of the ring.-* On examining a ring in which the clear and cloudy spirals are plainly distinguished, it will be found to have the appearance of *alternating layers or bands of cloudy and comparatively clear air arranged horizontally,* but which are most strongly marked towards the top and bottom of the ring, and cease to be discerned near the middle. When the air employed is only moderately cloudy, and the rings are large and perfectly developed, this banded appearance is admirably brought out by a mild transmitted light, and adds not a little to the beauty of the revolving and expanding wreath.

It is easy to see that this apparent structure is an *optical illusion* due to the passage of the light alternately through a greater and a less thickness of the cloudy lamina of the composite ring. Thus it will be observed (fig. 3) that the rays coming to the eye in the horizontal plane which passes through the upper part of the cloudy spiral will be much more obscured than those which pass in a parallel plane through the clear space immediately beneath, the former having to pass lengthwise through a considerable distance in the cloudy layer, while the latter traverse little more than twice its thickness. The same relations must hold for the next inner turns of the spiral, but as its circuit grows narrower the difference between the aggregate of clear and cloudy portions passed through must continually grow less, and near the equator of the ring become quite insensible; hence the bands which are so distinctly marked towards the top and bottom of the ring disappear as we approach its midway line.

6. *On the effects produced by a continuous blast.-* By slightly *prolonging* the impulse either

from the mouth or the bag so as to expel a comparatively large amount of the cloudy material at a moderate velocity we are able to mark the partial formation of a second ring in the swollen part of the train which still adheres to the first, and even of a third yet more imperfect one in the train prolonged below the second, the whole still forming a united mass.



With a *continuous and uniform blast* of moderate force the appearances are even more curious and instructive. The column in this case retaining its smooth cylindrical outline for only a short distance above the aperture, presents higher up along its sides, and at nearly equal intervals, a succession of whorls or volutes, more and more developed as we ascend, and which not unfrequently terminate at the top in a nearly perfect and separate ring, (fig. 4). On urging the blast with a much increased velocity these lateral markings of the column become less conspicuous, and assume throughout, nearly to the summit, the aspect of a series of short projections curving steeply downwards, like the lowest and least developed volutes in the preceding experiment.

On examining these lateral gyrations as shown in the figure it will be seen that each is formed at the expense of the adjacent parts of the column both above and below it. The central arrows pointing divergingly upward indicate the direction in which the inner portions of the stream are deflected to unite with the wider part of the spiral; the exterior arrows directed downwards mark the relatively retreating motion impressed by the resistance acting at the sides, and show the course of the particles passing into the spiral from above.

It would seem that these movements must have the effect, superficially at least, of dividing the column into alternate tracts of rarefied and condensed air, the former situated about midway between the successive coils, and the latter directly above where the coils unite with the main mass. These regular alternations, virtually equivalent to a system of waves or vibrations generated in the effluent stream, indicate the analogy in condition of large streams of gaseous matter, and the slender jet in which such vibratory movement has already been demonstrated, and point to one of the agencies which may be concerned in the latter phenomena. They at least furnish conclusive proof that *even a large stream of gas discharged under a steady pressure does not flow with continuous uniformity, but become the seat of periodical movements at equally recurring intervals.*

II. *Of the motion of the air produced by the rupture and by the explosion of bubbles.*

As the beautiful rings developed by the explosive combustion of phosphuretted hydrogen gas are formed under the influence of far more energetic forces than are brought into play by the rupture of a bubble of common air, it becomes important to determine what kind and amount of effect is due to the simple bursting of the bubble independent of any explosive action. I have, therefore, made numerous experiments on bubbles of common air rendered cloudy as in the previous experiments, and have been much interested by discovering that in all such cases a *distinct rotary motion is produced corresponding with that of the air rings already described.*

7. *Mode of experimenting with floating bubbles of air*.- In order to observe the movement of the air occasioned by the bursting of the bubble I use a deep glass bowl, into which is poured a layer of water containing soap enough to give durability to the bubbles when formed on its sur-

face. A finger bowl of the largest size answers for this purpose. Placing this on the table near the ring apparatus (fig. 1) previously charged with very opaque air, I attach to the tubulated aperture of the jar a flexible pipe terminating in a glass tube of about one-tenth inch in diameter. Dipping the end of the tube into the soapy water so that it may take up a short column of the liquid, I hold it centrally over the water and close to the surface. Then breathing carefully into the mouthpiece, provided for this purpose with a narrow opening, I form a floating bubble of any size from a half inch to three inches in diameter. This being done the glass beak is to be gently lifted away, and the bowl covered with a glass plate, brought over it with a sliding motion. The bubble must now be left undisturbed for fifteen or twenty seconds, to allow its contents and the air of the bowl to come to rest, at which time the suspended cloud will be seen to have subsided a little from the apex, showing a level surface above.

As it is necessary for a satisfactory observation that the rupture of the bubble should begin exactly at the top and extend symmetrically around that point, and as in the spontaneous bursting this only occasionally occurs, it is expedient not to wait for the rupture but to force it by means of a wire inserted vertically through the apex and quickly withdrawn, the glass cover having first been removed by a gentle sliding motion. When this has been done so as to avoid agitation we see a cloudy column rising some inches above the liquid, and rolling over in delicate volutes at the top.

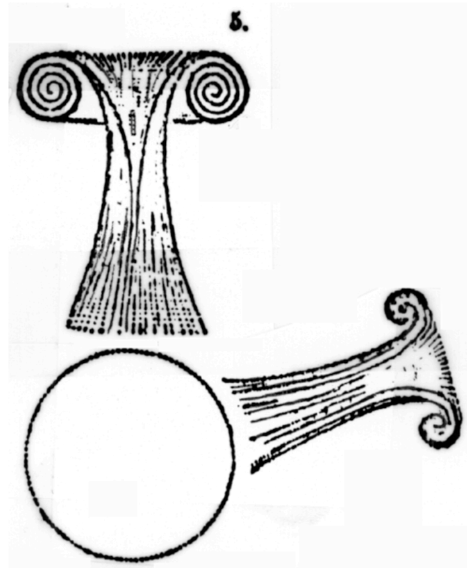
With a bubble of from one to one and a half inches in diameter the symmetry of the resulting column is quite striking and *its correspondence in motion and shape with that already described as an early stage of the ring formation is not to be mistaken.* In many cases a perfect and almost separate ring is developed at the top, and when the air is not too opaque the alternate coils and the resulting horizontal bands are perfectly distinct. But from the feebleness of the rotation these appearances are only momentary. When the bubble is two or three inches in diameter, the outward and downward curling at the top of the cloudy mass is still quite observable, although much less marked than in the preceding case. When very small bubbles are broken, the motion is too quick and the cloud too small for satisfactory observation.

(8.) *Origin of the rotation*.- It thus appears that in the mechanical rupture of a floating bubble forces are brought into play similar in kind and general direction to those operating on the ring-discharges from an orifice. Of these, one is evidently the *tensional action of the liquid film* driving the cloudy air through the opening, another is the *resistance of the adjoining air* into which the mass is impelled. The former corresponds in effect to the tension propagated through the reservoir in the previous experiments, the latter is the same in both cases; and we may consider the widening aperture of the bubble through which the air is thus as it were squeezed, as answering to the orifice on the top of the jar.

This view of the mode of action of the film is confirmed by the very curious effect which results when the bubble is punctured on one side. Thus applying the point of the wire near the base we see the cloudy column rushing out in a nearly horizontal direction on that side. If we pierce the bubble at an intermediate height the air is projected obliquely upward toward the hand. It can hardly be doubted therefore that in all cases *the bubble is destroyed by a progressive and regular enlargement of the opening first made, and that this takes place with sufficient slowness to allow the aperture to give direction to the extending force*.

(9.) *Rings generated from spherical bubbles*.-The effects just described are produced in a still more striking degree by the rupture of the bubbles of completely spherical form. In this as in the former experiments the utmost care must be taken to protect the adjacent air from agitation. With this view the bubble as soon as blown should be deposited at the bottom of the glass bowl on a piece of soft cloth or a flake of carded cotton, and left undisturbed for ten or fifteen seconds. On piercing it at the top with a very slender wire *we see its contents suddenly projected up wards some inches,* forming a cloudy column whose summit rolling over on all sides develops a *beautifully distinct ring* which at times ascends so rapidly as to separate from the general train.

The effect is best seen with a bubble of from three-fourths to one inch in diameter. When the contiguous air is perfectly quiescent the ring retains its form even above the top of the bowl, affording a clear though momentary view of its twofold spiral and the resulting horizontal bands, as well as of the direction of its rotation. When pierced at the side instead of the apex, the bubble, as might be expected, projects its contents towards that side in the direction of the wire, showing though less perfectly the same configuration. Both effects are rudely indicated in fig. 5.



As these experiments on the rupture of bubbles will be found to have much interest, I may suggest that they can be easily repeated by forming the bubbles with tobacco-smoke blown from the stem of a common pipe, from which they are readily transferred to the soapy water as spherical segments or to the cloth surface as entire spheres. But it must be remembered that even a slight motion of the contiguous air will defeat the observation.

I need scarcely add that the tensional action of curved films of liquid, so strikingly shown in these phenomena, has been illustrated by Prof. Joseph Henry in a series of interesting experiments of which an account was published some years ago.

In the present case the most important inference to be drawn from the results is that the destruction of the bubbles proceeds not from a subversion of cohesion irregularly throughout the film, but from a uniformly progressive enlargement of the opening first formed, by the continuous retraction of its edge.

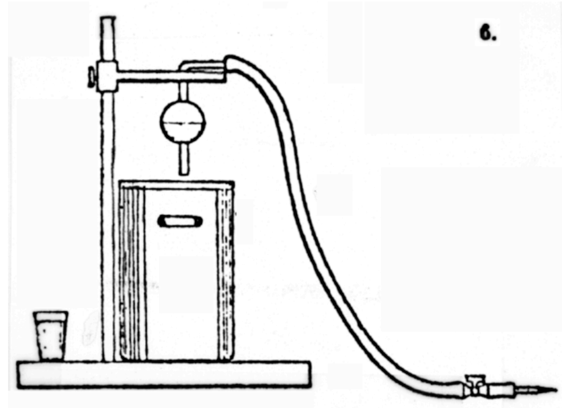
(10.) *Of the rings produced by floating bubbles of phosphuretted hydrogen gas, when exploded.*- In what has just been stated we mark the effects simply of the mechanical rupture of the bubble, calling into play as a motive agent the tensile force of the film, or what is equivalent, the expansive action of its contents released from the pressure under which they have been held. But in the present case the rupture has no sooner begun than a chemical action of great intensity sets in between the included gas and the air. This commencing usually at the apex and extending downwards and laterally *in a symmetrical manner* gives rise to a powerful expansive force having an obliquely upward direction on all sides. The products of the combustion are thus impelled into the contiguous and comparatively quiescent air under conditions very analogous to those of an energetic momentary discharge from the ring apparatus of the former experiments. The resistance at the sides of the ascending and spreading column, combining with the upward impulsion of the interior will, therefore, give rise to a *similar rotation of the cloudy mass,* rolling it up into the spirally constructed ring in which it presents itself at the close of the explosive action.

It will be remarked that these explosive rings are more rapid in their expansion as well as their rotation than the rings produced by mechanical discharge, a result due doubtless to the greater energy of the forces by which they are developed. As might be expected, rings of the latter kind approaches more nearly to the former in these particulars when a vigorous impulse is applied in producing them.

In most cases the wreath of phosphoric acid is so opaque as to preclude the examination of its interior structure, but when more diluted, we are able to trace within it, as in the other rings, the two-fold coil of cloudy and clear atmosphere.

In experimenting with the explosive bubbles every one must have noticed the frequent occurrence of irregularities and failures in the production of the ring. This is a natural consequence of the rupture beginning on the side or at more than one spot, instead of commencing at the apex of the film and accordingly in such cases it will be remarked that the flame and smoke dart out laterally, producing a broken and almost formless wreath.

III. *Of the formation of liquid rings.*



The production of liquid rings by a succession of drops, although only of occasional occurrence, has doubtless often been observed in the course of laboratory manipulations. Yet so far as I am aware no attempt has hitherto been made to determine, the structure and movement of these rings, or the precise conditions under which they are generated. My attention having been called to this class of effects by some remarks of Prof. Horsford on the rings formed by precipitated sulphate of lead, I was led after various trials with this and other precipitates to discard the chemical action as irrelevant to the particular effect in view, and do employ as a dropping-liquid water charged with some coloring substance, either suspended or dissolved. Among the materials thus used may be mentioned chromate of lead, carbonate of lead, sulphate of lead, sulphate of baryta, cobalt blue and dilute solution of sulphate of indigo. Of these, the two first and the last yield perhaps the most perfect results.

11. *Production of liquid rings by drops*.- A convenient apparatus for these experiments consists of a globular pipette (fig. 6) of about two inches in diameter, mounted on an arm which is capable of turning easily in a horizontal plane, and a large cylindrical vessel filled with clear water nearly to the brim. The beak of the pipette, about an inch in length, has a smoothly ground aperture of one-tenth inch. The upper tube, bent at right angles, is fastened into a flexible pipe about eighteen inches long, to the outer end of which is adapted, by means of a small stopcock and short gum-elastic tube, a slender tub of glass drawn to a fine capillary bore.

In order to charge the pipette, we revolve the horizontal arm into a convenient position, and bring the small vessel containing the colored liquid up to the beak. Then slipping off the coupling tube we apply the lips at the stopcock, pump up the charge and quickly closing the stopcock replace the coupling and capillary tube. After one or two drops have fallen the flow ceases and the pipette may be brought round over the centre of the reservoir. By opening the stopcock either partially or wholly we have perfect control over the rate of discharge, and can make the drops succeed each other as slowly as we please.

It should be observed that air bubbles carried by the drop into the liquid produce an irregular motion, destructive of the desired effect. Hence the beak should be placed only a short distance above the surface. An interval not exceeding one and a half inches usually answers very well, but at a distance of from one half to one inch admirably uniform results are obtained. Indeed, it is not necessary to the effect that the drop should reach the surface with any sensible velocity, as a well-formed ring will be produced by simply *laying the drop upon the water* from the closely approached beak of the pipette.

As it is essential to a perfect experiment to have the liquid of the reservoir as motionless as possible, its mass should be large, and it should be allowed to come to rest after each drop before the next is allowed to impinge upon it.

Operating with these precautions, and viewing the result from a point a little lower than the level of the fluid, we see that the drop, soon after merging in the liquid, gives origin to a ring of exquisite symmetry, which rotates and enlarges as it descends, precisely after the manner of the gas-rings already described. In some cases the ring, continuing unbroken through the whole depth, spreads out on the bottom a flat annulus of the heavy coloring matter. But usually, after reaching a distance of four or five inches, it breaks up with a peculiar outward uncoiling motion, forming at intervals of the circuit flattened spaces, from the outer points of which the pigment is seen dropping in numerous slender streams.

12. *Motions and structure of the liquid rings*.- The rotation of the liquid ring on its circular axis is directed upwards on the outer circumference and downwards on the inner; or viewed in relation to the progression of the mass, it presents an advancing movement of the inner and a retreating movement of the exterior periphery. It is thus identical with the rotation of a gas-ring impelled in a descending direction.

The liquid ring, moreover, resembles that of gas in being composed of a coil of colored fluid enfolding a parallel uncolored coil. Indeed, when sufficiently translucent, it exhibits quite distinctly the horizontal bands which, in the case of rings of cloudy air, have been shown above to be an optical result of this twofold structure. The correspondence between the phenomena is rendered still more complete by the fact, that the liquid ring is followed by a residualy colored mass, which, when the forming impulse is feeble, remains attached to it as a train.

13. *Formation of liquid rings by impulsive discharge*.- The observed identity of motions and structure in the two classes of rings led me to attempt the production of liquid rings by a mechanical process similar to that used in forming the rings of air. For this purpose I lowered the beak of the pipette so as to immerse it a little below the surface of liquid in the reservoir, and closing the stopcock applied a sudden and transient pressure of the fingers to the flexible tube. The experiment was eminently successful. The colored liquid thus discharged was seen to shoot downwards in the form of a very perfect ring, in all respects resembling those above described, except that its rotation and expansion were more rapid. Modifying the arrangement by attaching to the stop-cock a small but thick gum-elastic bag, I have found it easy to regulate the impulse so as to develop the rings as slowly as may be desired, and thus to reproduce with the colored liquid all the stages of the phenomena previously marked in the case of rings of air. In this way, by a gentle and rather gradual force, I can cause the escaping fluid to rise up intolateral volutes, or, increasing the action, to form the opening ring with its attached train; or, by a yet quicker and stronger impulsion, I can compel the ring to shoot rapidly away, leaving the train either to break up irregularly or to form by its own motion, a second smaller ring, as in the case of discharges of air.

The rings thus formed in the midst of the liquid will, of course differ in size, according to the amount of liquid expelled at each impulse. As, however, this is never so small as a drop, and the velocity of the action is comparatively great, the rings thus formed are always larger than those resulting from the dropping process. They are, therefore, better suited for observations on the internal motions and duplicate structure of the liquid ring. It is essential in such observations, however the ring may be formed, to make use of a partially transparent liquid, such as a dilute solution of sulphate of indigo, or a thin mixture of cobalt blue, and to view the ring by a moderately strong light. In these circumstances the double spire and the horizontal bands become beautifully apparent.

14. *Origin of the liquid ring, and of its rotation*.- Considering the entire agreement in structure and motions of the liquid ring as compared with the mechanically formed ring of air, it is natural to conclude that similar conditions of force are concerned in their production. Such is evidently the fact with rings generated by the process last described, that is, when the orifice is at or below the level of the reservoir. Here, the impulse of discharge acting downward and laterally, and the resistance of the aperture and of the contiguous medium acting backwards, present a combination of forces precisely such as, according to the previous explanation, operates in the production of the rings of air.

In regard to the formation of rings by the dropping process, the mechanical conditions, although apparently different, are such as I think would naturally give rise to the same combination of motions. In considering the mode of action of the drop it is proper to distinguish between the case of a drop which *impinges upon the surface* of the medium with a sensible velocity and that of one *simply laid upon it* from the beak of the dropping tube. The former strikes the medium with the acquired momentum, and penetrating into it as if through a circular aperture, forms an advancing column whose central parts are carried forward, while the sides are relatively retarded by the resisting action of the contiguous fluid. Under these conditions, the forces brought into play and their resulting motion must evidently be the same as in the case of an impulsive discharge of liquid from the immersed beak of the pipette.

In the other case, that is, where the drop is simply laid upon the liquid plane, the gravity of the matter of the drop and the tension of the curved surface unite in giving a downward impulsion to is contents. At the same time, the surface of contact with the fluid beneath, forming, as it were, a rapidly enlarging circular aperture, secures the symmetry of the moving mass. This, as it advances, will of course be subject to the same moulding action of the impulsive and retarding forces which has just been described, and which, as we have seen, imparts to rings of air and water formed by mechanical discharge their identity of structure and motion.