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SCIENCE

CURRENT PROBLEMS IN RESEARCH

Collision Characteristics of Freely Falling Water Drops

With the use of new apparatus, collisions have been photographed and classified into five basic types.

Ross Gunn

The basic physical processes associated with the formation and subsequent free fall of rain have been inadequately studied, and many features are still poorly understood. Basic questions related to the conversion of clouds into rain remain unanswered. Other fundamental questions regarding the electrification of rain and its relation to thunderstorm electricity emphasize the large gaps in our present understanding of precipitation mechanics. It has been clear for some years that the behavior of raindrops during and after collision is likely to have important consequences for the description of rainfall characteristics.

It was not clear at first how these problems could be attacked experimentally to produce meaningful data. However, recent development of special apparatus has made possible an exploration of these processes, which are described herein. The elements of the technique adopted in my laboratory were tried out more than 10 years ago, but only limited success was achieved because the reproducibility of position of successive falling drops was inadequate. These early measurements attempted to use drops so small that the inherent irregularities largely defeated our objective. The development of an improved device for producing and serially dispensing a continuous series of medium-to-large water drops has permitted a variety of detailed direct visual examinations of collision phenomena. High-velocity large-drop collisions are frequently spectacular and beautiful when viewed in the laboratory with the aid of an electronic stroboscope.

The present technique has been sufficiently developed to illuminate the principal features of drop collision mechanics under a wide variety of circumstances. The technique promises to be capable of extension into the area of cloud droplet dynamics. Our preliminary explorations have been made possible through the development of an improved "synchrodropper." This device is designed to dispense serially water drops of substantially uniform size at uniformly spaced time intervals. By exercising special care with certain details, satellite drops are largely avoided, and the reproducibility of successive drop positions is quite satisfactory. Two such synchrodroppers correctly positioned and adequately controlled and synchronized by special circuits permit a tremendous number of controlled collisions between two freely falling drops to be observed in a short time.

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The Synchrodropper

Vibrating reed drop dispensers have been described (*1*), but none were found suitable to dispense medium-to-large liquid drops reproducibly when operating in close harmony with a second synchronized dropper. A suitable synchrodropper of heavy construction is suggested in Fig. 1. A laminated transformer core having a cross section of 6.45 square centimeters is modified, as shown, by sawing off one leg and mounting the core securely on a heavy base. A vibrating steel spring S, 0.12 to 0.16 centimeter thick by 2.5 centimeters wide, is supported by a heavy clamp D so that the spring overhang can be adjusted to establish an approximate resonance with the a-c driving power. On standard power circuits the spring may be driven at either 120 or 60 cycles per second. We usually prefer the low frequency mode which may be excited by mounting a standard Indox ceramic magnet as shown at M. This magnet is magnetized along the short axis and is effective in permanently polarizing the magnetic circuit. On the free end of the spring is mounted a brass jet T which has a hole 0.25 centimeter in diameter. Large water drops are dispensed directly from this jet. The outside of the jet is tapered to accept standard hypodermic needles which are cut down and ground square on the end to dispense the smaller drops.

The open leg of the modified transformer core is wound with 2000 turns of No. 28 B-and-S enamel wire which is connected directly to the output of a controllable autotransformer as shown in Fig. 2. The air gap between the permanent polarizing magnet M and the spring should not be less than about 0.16 centimeter, and vibration to contact with the core should not be allowed. A useful auxiliary for the study of electrical effects is the insulated inducing electrode C arranged to surround that point in the liquid jet where the jet first breaks up into drops. Electrostatic charges up to 0.1 electrostatic unit are easily placed on

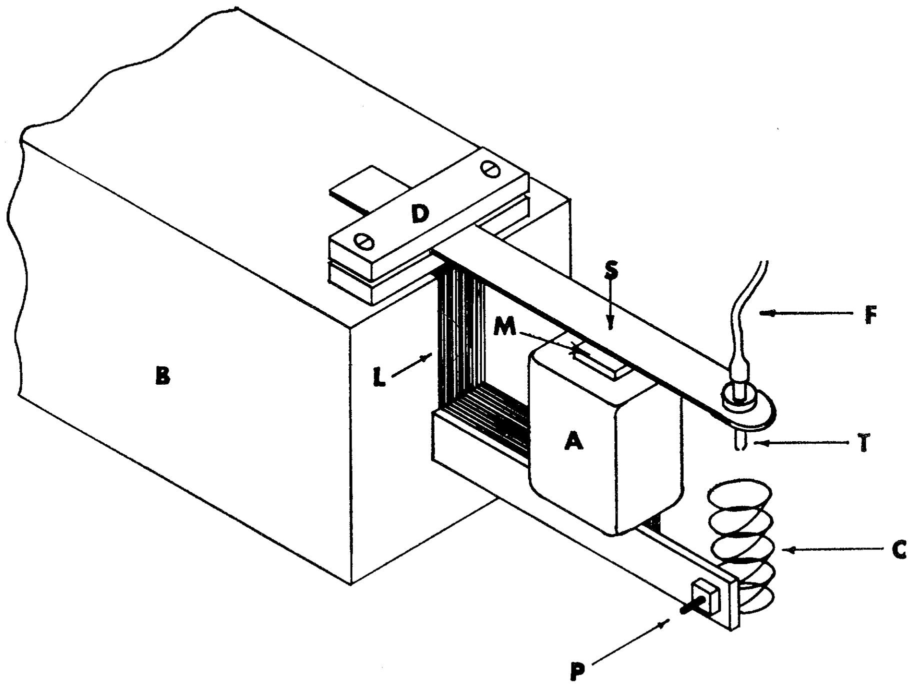


Fig. 1. Construction features of a stable synchrodropper. See text for interpretation of letters.

each drop by applying potentials up to 300 volts direct current on the electrode while the other pole is grounded to L.

Since the usefulness of the synchrodropper depends on its ability to release the drops in exact and reproducible synchronism, much effort has been devoted to understanding and minimizing the causes of irregularity. As examples of small matters that require attention to secure the best performance, it is necessary that the jet be connected with a constant-level water supply by a very flexible tube. The water flow from the 0.6- or 1-meter pressure-head maintained above the jet is regulated by a brass needle valve. The water in some localities should be deaerated so that no bubbles cling to the jet or connecting tubing. No vertical loops should be permitted in the tube feed. The jet must be so oriented that its axis is parallel to the trajectory of the projected drops. Axial vibrations of the spring must be eliminated. Experience shows that there is always an adjustment of the driving coil voltage and the water flow that gives satisfactory performance. Correct operation of a synchrodropper should produce drop series like that shown in Fig. 3. In this figure time increases from right to left. The reader should notice the motion of the jet as well as the acceleration of the falling drops.

In the present investigation, we employ two interconnected synchrodroppers. Since both droppers operate off the same power system, the drop frequency is always the same, but two streams of drops describing intersecting trajectories usually do not collide with each other. In order to control the collisions, it is necessary to control the relative phases of the synchrodropper pair. This is best accomplished by the method shown in Fig. 2. One dropper is operated through an adjustable autotransformer directly off one phase of a three-phase power circuit. The other dropper is excited by way of an adjustable autotransformer that derives its power from a single winding on a three-phase wound armature motor so arranged that this winding may be exposed to any desired phase component of the main rotating stator field. The armature is normally locked, but the phase can be advanced or retarded by turning the armature to the desired position. A three-phase differential selsyn motor may also be so modified as to be useful in place of the three-phase motor above. Electrical control of the phase is a great convenience, but if the experimenter has sufficient patience, he can adjust the relative phase of the falling drops by mechanically shifting the position of one synchrodropper with respect to the other.

The synchronized falling drops are observed or photographed with the aid of a high-intensity electronic stroboscope whose frequency can be maintained exactly at or slightly above or below the characteristic frequency of drop release. The General Radio Type 1531A strobotac has been found quite satisfactory. Because the "jitter" of the drop position can be kept small, the character of the deformation for any particular impact geometry may be observed at the rate of 3600 events per minute. A careful observer can witness many interesting and informative events with the use of this apparatus.

A series of explorations have shown that one of the main problems to be considered in any analysis of formation

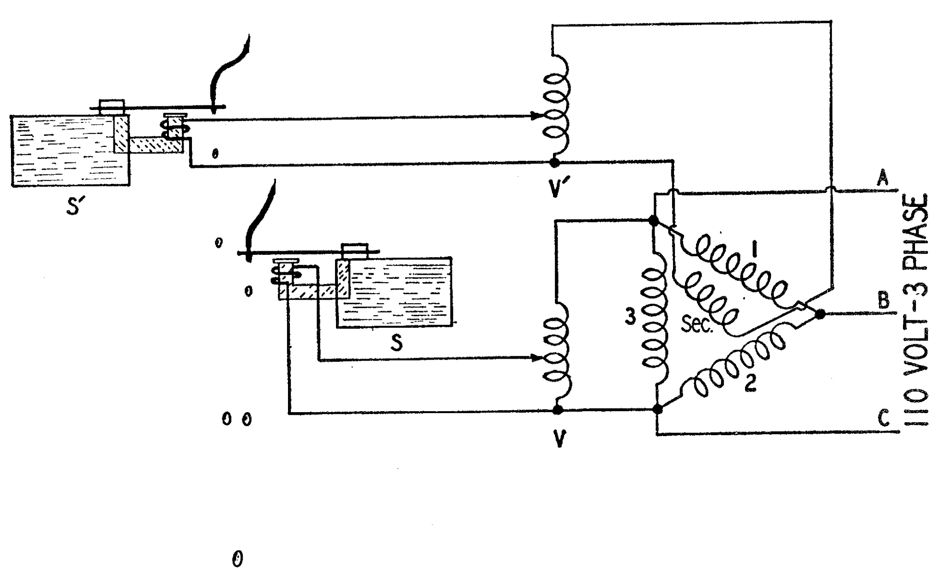


Fig. 2. Electric phase control and power circuits for a synchronized pair of droppers. See text for interpretation of letters.

and subsequent transfer of rain to the ground is the problem of drop collision. Collisions are important in the growth of cloud droplets into rain. Collisions play a part in the interaction of freely falling rain drops to establish the drop size distribution, as well as a vital role in the production and exchange of free electricity in an active thundercloud. Our investigations show that there are five identifiable types that should be independently considered in evaluating the importance of collisions. Some of these types may be influenced by free electrical charges on the drops. The principal types are (i) collisions resulting in drop recoil, (ii) collisions with resulting drop coalescence, (iii) collisions resulting in drop disruption, (iv) collisions producing drop spatter, and (v) hailstone collisions. Certain special cases are dynamically most interesting, but probably not too important in the rain-production processes.

In order to evaluate the importance of collision processes in the free atmosphere, it is necessary to determine whether there are enough drop collisions under typical rain conditions to grossly influence weather processes. The rates are readily calculated by making two simplifying assumptions. First, one assumes there are only two classes of drops and sizes which interact with each other, and second, that the active collision area is simply the projected geometrical area. The results of such calculations are clearly incomplete, but are readily corrected by summing up the collisions between the drops in the various size pairs. I have already very briefly worked out the principal influences of drop electrification on the effective collision cross section (*2*).

Consider the interaction and collisions between two sizes of rain drops. Suppose there are N large drops per cubic centimeter, each having a mass M, a radius A, and a vertical terminal velocity of fall U. Similarly, let the number per unit volume of the smaller drops be n, terminal velocity u, mass m, and their radius a. It is usually convenient to express the number of drops per unit volume in terms of the liquid water content per unit volume (LWC) with a subscript appropriate to the size of drop considered. Thus $NM = (\mathrm{LWC})_N$ and $nm = (\mathrm{LWC})_n$.

Consider the freely falling water drops in a prism of unit cross section extending vertically through the precipitation region, and assume that the population densities of the two interacting drops within this prism are uniform. (We ignore the improbable case in which the smaller drops might overtake the larger, faster-falling drops.) The collision volume swept out per unit time dV/dt by a single large drop is

$$\frac{dV}{dt} = \pi (A + a)^2 (U - u) \quad (1)$$

where $U - u$ is the *relative* velocity between the moving drops. Now the number of collisions per second between a single larger drop and the smaller drops is clearly the ratio of the volume swept up by the larger drop to the mean volume occupied by each smaller drop $1/n$. Thus if N' refers to the number of collisions, it is found that for a single larger drop the number of collisions per unit time is

$$\frac{dN'}{dt} = \pi (A + a)^2 (U - u) n \quad (2)$$

Thus since there are N large drops per unit volume, the number of collisions per unit time and per unit volume is

$$\frac{dN'}{dt_V} = \pi (A + a)^2 (U - u) n N \quad (3)$$

The distance that a larger drop falls in the free atmosphere in a given time t is Ut, and the distance it falls relative to the slower smaller drops is $(U - u)t$. Therefore, the distance that a single larger drop must fall to experience a single collision is

$$Z_{\mathrm{coll}} = \frac{U}{\pi (A + a)^2 n (U - u)} \quad (4)$$

This is the mean collision distance for each of the larger drops.

In a similar way the mean time τ between collisions for a single drop is

$$\tau = \frac{1}{\pi (A + a)^2 n (U - u)} \quad (5)$$

If numerical values typical for heavy rain at the earth's surface—namely, $A = 0.08$ cm, $a = 0.04$ cm, $U = 565$ cm/sec, $u = 327$ cm/sec, and a LWC $= 10^{-6}$ g/cm^3 for both drop sizes (*3*)—are substituted in the above expressions, it is found that the number of collisions per unit volume and unit time approximates 1.8×10^{-5} collisions per cubic centimeter per second. The larger drops collide, on the average, 7.6 times in falling every kilometer. The mean time between collisions is 23 seconds. Since every rain drop falls several kilometers, it is clear that a great many collisions take place. It is clearly important, therefore, to examine the physical characteristics of collisions and their fundamental influence on atmospheric processes.

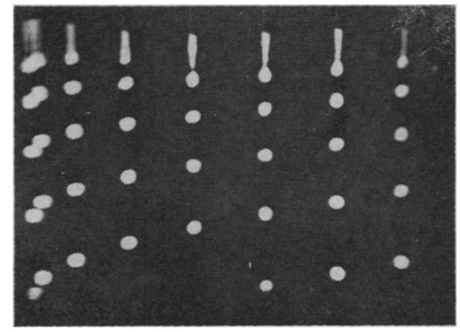


Fig. 3. Proper performance of a stable synchrodropper. Time increases toward the left. Notice the acceleration and motion of the jet.

Collision with Recoil

We have examined in some detail the collisions between water drops having radii in the neighborhood of 0.1 centimeter. If the relative velocity between the two colliding drops is less than about 40 centimeters per second, the two drops approach each other, interacting sufficiently to produce a visible deformation of each drop, and then recoil *without* coalescence or

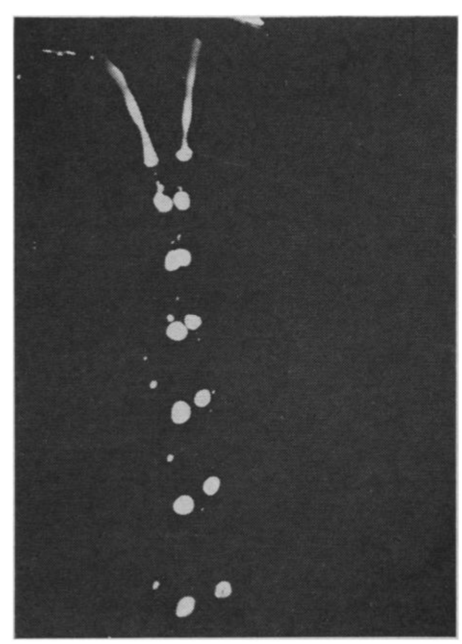


Fig. 4. Drop collision with recoil and separation. Relative velocity less than 40 cm/sec.

without contact sufficient to extract water from either drop. This elastic behavior is well illustrated in Fig. 4 and is due to the surface tension of the drops. The observed deformations suggest that the difference between the kinetic energies of the drops is insufficient to disrupt the surface-tension layer and thereby permit coalescence.

It is well known that the pressure p inside a spherical drop of radius R, due to surface tension phenomena, is

$$p = \frac{2T}{R} \qquad (6)$$

where T is the surface tension. Thus the work necessary to form a spherical drop of radius R is

$$W = \int_0^R p\mathrm{d}V = 4\pi R^2 T \qquad (7)$$

where $\mathrm{d}V$ is the element of volume. This is a minimum energy, and any gross distortion of the drop, such as that necessary to penetrate it, will require from any colliding drop a kinetic energy nearly equal to, or greater than, that given in Eq. 7. Suppose a drop of mass m and radius a approaches a larger drop of radius R at a relative velocity U. A gross deformation of the larger drop sufficient to permit the incorporation of the volume of an approaching drop will require that the relative kinetic energy approximate

$$\begin{aligned} \tfrac{1}{2}mU^2 &= \left(\frac{2\pi}{3}\rho a^3\right) U^2 \geq \int p\mathrm{d}V \\ &\doteq \frac{2T}{R}\int \mathrm{d}V \doteq \frac{2T}{R}\left(\frac{4}{3}\pi a^3\right) \end{aligned} \qquad (8)$$

where ρ is the liquid density. Conversely, if the relative kinetic energy of the impinging drop is less than the threshold defined by Eq. 8, the collision is elastic and the oncoming drop recoils without coalescence, as shown in Fig. 4. For convenience, Eq. 8 may be put in the form

$$U' = \left(\frac{4T}{\rho R}\right)^{\frac{1}{2}} \qquad (9)$$

where U' is the critical velocity separating the recoil and coalescence regimes. The relation is clearly an approximation, since the exact form of the deformation is usually unknown. Equation 9 has been plotted in Fig. 5. Within a rather large experimental error, we find that Eq. 8 is in accord with our observations and measurements. It is clear from our observations on large drops that drop association is not guaranteed by actual contact and that special energy requirements must be met before coalescence takes place.

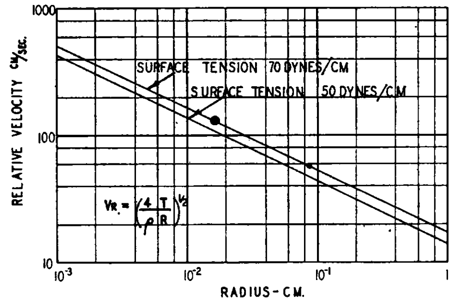


Fig. 5. Critical value of the relative collision velocity as function of the radius of the larger drop. Collisions having parameters below the curve recoil without coalescence. (The points on the curve are used as benchmarks in other work.)

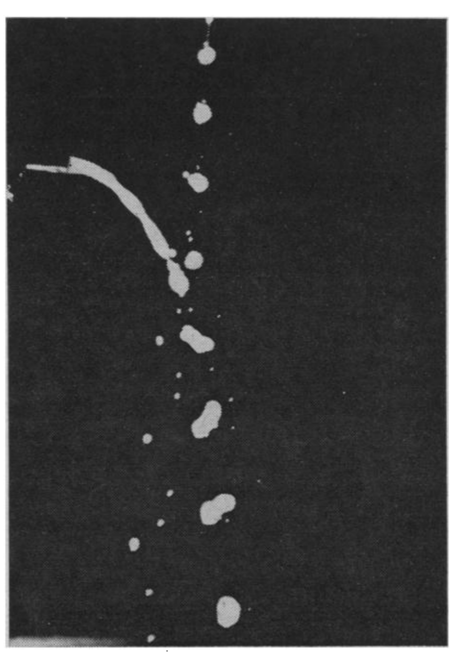
Before we leave this aspect of collision phenomena, it is necessary to note an exception. We have observed that two drops of the same size falling vertically side by side at nearly the same velocity *do* associate. Strictly speaking, this is not a collision, since the relative velocities are zero. It is thought that coalescence is due to the Bernoulli pressure reduction in the regions between the drops or, possibly, due to energetic oscillations of the drop surface. An electric field transverse to the trajectories also promotes association. This special case has not yet been examined with any care.

Collisions with Coalescence

Whenever the relative kinetic energy of an approaching smaller drop appreciably exceeds $4\pi R^2 T$ for the larger drop, then the probability that the drops will coalesce upon a direct or centered collision becomes great. A simple case of such a collision with coalescence into larger drops is illustrated in Fig. 6. Our observations emphasize that approximately central collisions are usually necessary for coalescence to take place. Eccentric or glancing collisions almost always result in some sort of disruption of the drops. Actually the range of relative kinetic energy necessary to promote coalescence is rather limited because when this energy is adequate, inertial forces play an appreciable part. During a collision, the frictional forces due to viscosity are generally small in comparison with the inertial forces, but viscosity does play a part in attenuating the rather large drop oscillations that are commonly produced.

Collisions with Disruption

Collision with disruption is the most frequent and important in the free atmosphere, principally because of the prevalence and high probability of off-center impacts. Whenever the relative kinetic energies between the two col-



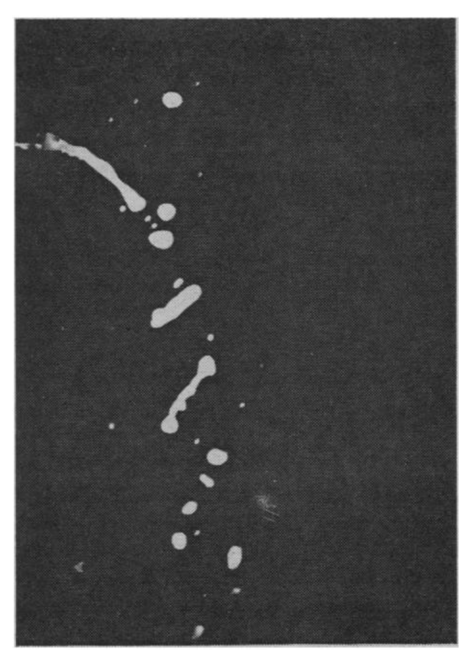
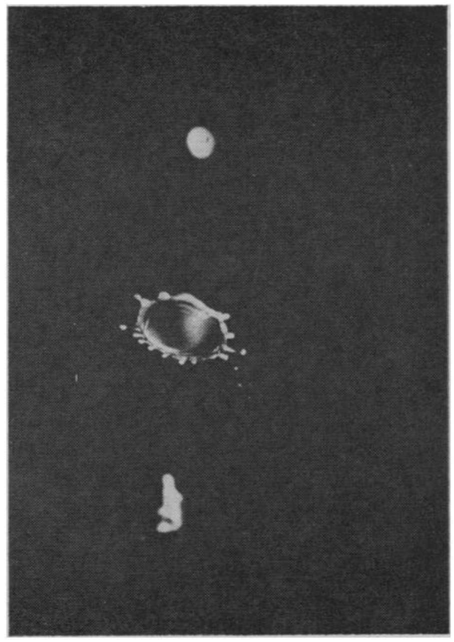


Fig. 6 (left). Collisions with drop coalescence. A nearly central impact is usually required for coalescence. Fig. 7 (right). Collision with disruption and breakup. Eccentric collisions favor this process.

liding drops exceed a few times the values specified by Eq. 8, a disruption of the drops is invariably observed. The exact deformations produced depend critically on the relative trajectories of the drops at first contact. The drop may be sheared or be rotated to produce several small drops, or the oncoming drop may appear to penetrate and emerge from the far side. Frequently, the drops make contact, and upon their separation, cohesion pulls the drops out into an elongated ellipsoid four or five times longer than the diameter of either of the original drops; and the assemblage immediately thereafter separates into a linear system of smaller drops. An example of such a typical collision pattern is shown in Fig. 7. About all one can say quantitatively about such collisions is the obvious fact that the momentum of the system is approximately conserved.



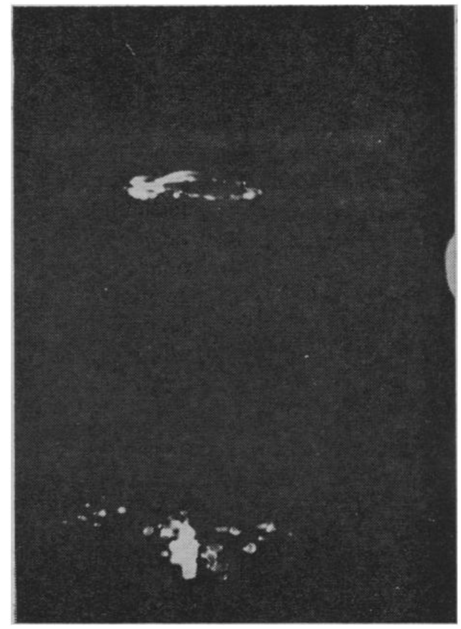


Fig. 8 (left). A central collision with spatter. Notice the web or plate closing the inner rim of the peripheral torus. Fig. 9 (right). A horizontal view of a central collision, with spatter. The web or plate is deformed upward while the spokes or nodules lie in a horizontal plane. Notice the assemblage of drops at the bottom of the picture; these are the residue from the immediately prior collision.

Collisions with Spatter

When the relative velocity of two medium or large water drops approximates or exceeds 200 centimeters per second, a value quite common even in moderate rainstorms, spectacular deformations of the drops are observed. A number of examples of such deformations are shown in the accompanying figures. Unfortunately, it has been necessary to mix milk with the water drops so that they can be successfully photographed. Typical spatter collisions are shown in Figs. 8, 9, and 10. The milk reduces the surface tension, and as a result the photographs do not correctly reflect the normally beautiful lacelike character of the deformed drop peripheries. Direct visual observation with a high-intensity electronic stroboscope shows numerous details which I have been unsuccessful in photographing.

Perhaps the most interesting collision geometry we have observed may be illustrated by two drops of approximate radius 0.22 and 0.20 centimeter. The larger drop is allowed to fall vertically, attaining a velocity of 450 centimeters per second, and is arranged to strike squarely the smaller drop falling at about 110 centimeters per second, so that the relative velocity at collision was 340 centimeters per second. The drops are first seen to make contact as spheres; they are then deformed into oblate spheroids. Next a small collar develops around the area of contact, and this shortly expands to form a thin, transparent, nearly circular plate in a plane perpendicular to the common axis, with spikes, arms, and nodules distributed around and extending away from its periphery. This plate may be five or six times the diameter of the original drops. Examination shows some of the tiny droplets are expelled radially at quite high velocities. As soon as the plate is fully formed it starts to shed droplets from the nodules at the periphery and to shrink, forming a constantly thickening peripheral torus from the available water, while the original plate persists inside the torus to form a transparent web or occlusion traversed with many tiny, axially symmetrical, circular waves. Thereafter, the torus continues to shrink and thicken until it breaks up into a large number of droplets. A photograph of such a collision is shown in Fig. 9. In this figure, attention is drawn to the assemblage of droplets below the occluded torus. These drops represent the end product of the dissociation of the torus formed 1/60 of a second earlier.

By employing the same drops mentioned in the foregoing paragraph but increasing the relative velocities to 450 centimeters per second, still more energetic effects are observed. The same platelike structure is at first produced and may now have a diameter 8 to 10 times the initial diameter of either drop. Long stringlike arms are now produced at the periphery of the plate, and the total diameter may approxi-

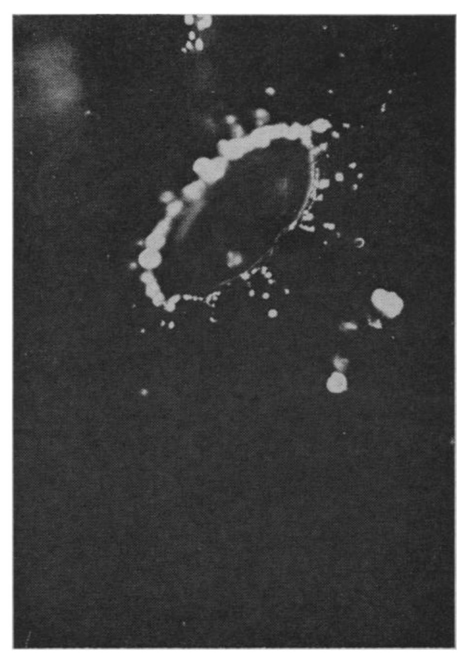


Fig. 10. Energetic collision with spatter. Relative velocity of two drops of 0.2-cm radius was 450 cm/sec. The nearly transparent web or central plate fills the thin torus forming at the periphery.

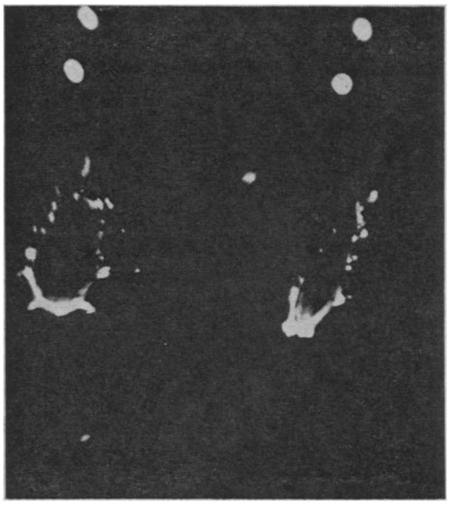


Fig. 11. Successive asymmetrical collisions with spatter. The contracting periphery develops an elliptical torus.

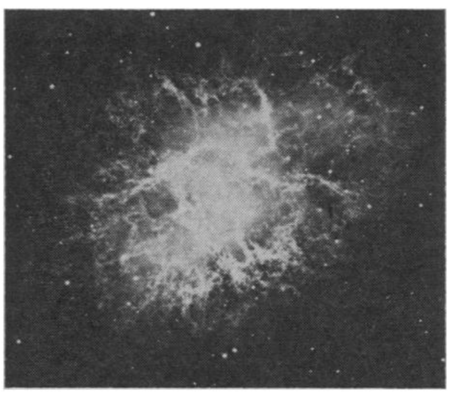


Fig. 12. The Crab Nebula in Taurus. This nebula energetically emits radio noise, x-rays, and possibly gamma rays. The motion of many of its parts away from its center suggests a recent collision and disjection.

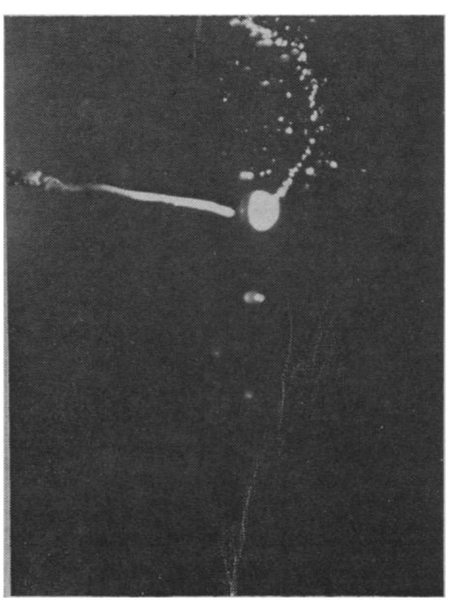


Fig. 13. Simulated high-speed hail-water drop trail.

mate 12 original drop diameters, as shown in Fig. 10. Although the plate still contracts toward its center, the actual amount of water accumulated at the periphery is now rather small, and the torus is rudimentary. In the previous cases the resulting small drops tended to concentrate near the original trajectory of the drops, but now they are still smaller and widely distributed over a distance of perhaps 15 radii of the initial drops.

If the above drops collide asymmetrically instead of centrally, an elliptical torus is formed whose plane is tipped toward the vertical and which is thicker on either the upper or lower side. The web internal to the torus is still preserved. Such a collision is shown in Fig. 11. The elliptical torus usually shrinks from its maximum extension asymmetrically and generally produces a rodlike distribution of final droplets. This distribution tends to be notably tipped toward the vertical.

The collision forms observed with disruption and spatter are endless. At high velocities the initial platelike form tends to become threadlike, first at the periphery and finally throughout, reminding one strongly of the well-known and beautiful pattern of the Crab Nebula in Taurus (Fig. 12). Whether the two end products are genetically related awaits further observation and measurement.

Collisions with Hail

The techniques outlined in the above paragraphs are not adapted to the study of drop collisions with hail. A typical hailstone falls at a velocity around 1000 centimeters per second and may have a mass of a gram or more. Collisions with hail are therefore unusually energetic. In order to assess the character of the interaction of a hailstone with a water drop, we arranged to drive a ball 1 centimeter in diameter on the end of an arm rotated by a synchronous motor at a linear speed of 1000 centimeters per second. A synchrodropper was so positioned that drops with radii of 0.2 centimeter fell through the region where the rotating ball was moving *downward* at the above speed. The downward velocity of the water drops was 400 centimeters per second, so the rotating ball overtook the freely falling water drop at a relative velocity of 600 centimeters per second. This arrangement closely approximates the collision of a hailstone overtaking a slower-moving water drop.

At first contact there is considerable spatter of tiny water droplets that are driven to the side. But shortly the drop makes full contact with the ball, wets and adheres to it, and trails upward with respect to the ball in a long stream that immediately disintegrates into droplets. The character of the water trail resulting from such a collision is shown in Fig. 13. In interpreting this figure, the reader should remember that the ball is rotating so that the trajectory of the traveling stream is also curved. The stream would extend vertically upward from a freely falling hailstone.

Modification by Electrical Forces

The only clear-cut electromechanical effect regularly noticed in our series of measurements occurred when the drops normally collided with such energies that they subsequently rebounded. Under these conditions the superposition of an electric field of about 400 volts per centimeter always suppressed the rebound and promoted coalescence. It is clear that such a field induces large electrical charges of opposite sign at the poles of each drop and that these charges interact with the charges on the other droplets at close range to modify their trajectories. The same effect was observed if the approaching drops carried free charges.

Superimposed electric fields or free drop charges usually produced no observable modification of the other types of collisions mentioned above. The free charges were observed, however, to modify the normal trajectories and the probability of collision between oppositely charged drops. These observations are consistent with an earlier conclusion suggesting that atmospheric fields comparable to 600 volts per centimeter are required to increase grossly the probability of charged-raindrop collisions (*2*).

Electrification of Collision Remnants by Induction

When any two insulated conductors are separated in an electric field, free static charges of equal magnitude and opposite sign are always generated. For example, consider two conducting spheres of radius a in contact and exposed to an electric field E_0 oriented parallel to the axis joining them. The free static charge Q induced on each sphere can be shown to be

$$Q = \frac{\pi^2}{6} E_0 a^2 \qquad (10)$$

Upon separation, one of the spheres will be positively charged and the other negatively. This mechanism is important in rain areas if collisions occur as frequently as our present estimates suggest.

On the cover of this issue a special case is shown in which one drop overtaking another accelerates it downward but is itself retarded. Such a specialized collision and recoil taking place in an impressed electric field induce free charges of opposite signs on the drops that later contribute to an increase in the magnitude of the impressed field. This special mechanism may be important in describing certain aspects of thunderstorm electricity.

The outstanding observed characteristic of thunderstorm rain is the fact that nearly equal amounts of positive and negative free charge are brought down on the raindrops and, moreover, about half of the drops carry large positive charges whereas the other half carry large negative charges (*4*). We have shown further that on the ground below thunderstorms the charges brought down on the drops are related to their radii by an expression of the form of Eq. 10, but with a different coefficient (*5*). We are persuaded that this outstanding parallelism implies that raindrop collisions resulting in disruption play an important role in thunderstorm electricity.

Summary and Conclusions

The development of a practical method for serially and reproducibly dispensing pairs of medium or large water drops and arranging for their collision during free fall in synchronism with an electronic flash stroboscope has permitted a visual study of the basic collision processes. The main collision types which are controlled by the relative kinetic energies include (i) elastic collisions resulting in drop recoil, (ii) collisions resulting in drop coalescence, (iii) collisions resulting in drop disruption, (iv) collisions producing drop spatter, and (v) hailstone collisions. In typical heavy rain, it is estimated that seven collisions occur for every kilometer of free fall. This is frequent enough to influence the drop size distribution and through inductive effects the electrical properties of the entire rain cloud.

Surface tension plays an important role in determining whether drops associate during collision, and its influence has been quantitatively estimated. Drop disjections by hail are of special importance.

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Symmetrical Gaits of Horses

Gaits can be expressed numerically and analyzed graphically to reveal their nature and relationships.

Milton Hildebrand

A gait is a manner of moving the legs in walking or running. The objectives of my research are to devise precise methods for describing and contrasting quadrupedal gaits, to survey the gaits of vertebrates, and to interpret the gaits used by particular species in relation to speed, body conformation, body size, maneuverability, and ancestry. This article presents results for the best-documented species, the horse. This master cursor has received particular attention because it is readily available, its locomotion is more controllable than that of other animals, and at the hand of man it has learned to be versatile in the selection of gaits and also to use gaits (termed artificial) that are unnatural to the species and unique to itself.

In symmetrical gaits the footfalls of a pair of feet (fore or hind) are evenly spaced in time. The walk, trot, and pace are symmetrical. In asymmetrical gaits the footfalls of a pair of feet are unevenly spaced in time. The gallop is an example. All gaits are under study, but asymmetrical gaits, having more variables, are more difficult to describe briefly and are not treated here.

In the 1880's, Muybridge triggered a battery of still cameras to take sequential photographs of the motions of 25 kinds of mammals (*1*). He noted that for each manner of moving, combinations of support by the several legs follow one another in a given sequence. Thus, for a walking horse, support by both hind legs and the right foreleg is followed by the left hind and right fore, which is followed by the left hind and both fore, and so on for five other support patterns before the cycle is repeated. I call any given sequence of this nature a *support sequence*. Muybridge recognized four principal support sequences for symmetrical gaits of horses. He represented each by a group of stylized diagrams (*2*) which, however, did not show the relative durations of the support provided by the various combinations of legs and did not assess variation.

Applications of this method have been somewhat extended (*3*), and one investigator attempted other correlations among the gaits (*4*). It is remarkable, however, that in spite of the advent of the motion picture camera

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