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Charge Transfer between Raindrops

Microwave temperatures of thunderstorms can be deduced from radiation emitted by colliding drops.

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Highly and oppositely charged pairs of water drops discharge upon close approach, emitting minute quantities of light and electromagnetic energy of microwave and ultrahigh frequency (UHF). The discharge threshold has been studied in the laboratory as a function of charge and drop size, and the magnitude of the change in dipole moment has been measured. By use of observations of natural free charges on drops in thunderstorms, the number of discharges expected per second per unit of cloud volume can be computed. On the assumption that the discharge events occur randomly in space and time and by use of the measurements of dipole moment, an apparent temperature due to discharging drops is computed for thunderstorm rain. The results may apply to the microwave temperature of the planet Venus if the clouds that obscure its surface exhibit the usual charged characteristics of aerosols.

Experimental Results

Streams of drops were produced in the laboratory by modulation of the rate of flow of water through a pair of hypodermic needles (*1*). The needles were connected to the terminals of an adjustable source of electric potential, which controlled the amount of charge on the drops. Spectrographic analysis of the light from the discharge between pairs of drops shows that its predominant source is the neutral nitrogen molecule (*2*). The light from a single discharge is too faint to be identified photographically, but the encounter of successive pairs of drops is sufficiently reproducible to permit multiple exposures. The cover photograph shows the result of a multiple exposure to the air-discharges from approximately 200,000 encounters between drops having a radius of 0.08 millimeter and a charge of 7×10^{-12} coulomb. Superimposed on this time exposure is a single-flash silhouette revealing the location of the drops a few microseconds after discharge. The bright spot immediately to the right of the second drop from the bottom of the left-hand stream is a positive corona that seems to be triggered instantaneously by the main discharge between the colliding pair just below. The triggering agent may be ultraviolet radiation from the main or parent discharge, or the change in electric field due to this discharge.

The spark-like process reduces the electric dipole moment of a pair of discharging drops by the amount Δp, which has been measured by having the discharge take place between parallel plate electrodes, spaced about 1 centimeter apart, connected to a sampling oscilloscope; the plates were so oriented that they were perpendicular to the line of centers of the pair of sparking drops. Electrostatic theory relates the flow of charge measured this way to Δp, the change in dipole moment of the drops. Values for Δp ranging from 3×10^{-15} to 5×10^{-14} coulomb-meter were obtained for drop charges from 3×10^{-11} to 1×10^{-10} coulomb and for drop radii ranging from 0.27 to 0.58 millimeter. The duration of the signal displayed by the sampling oscilloscope indicates that the duration 2τ of the spark is probably less than 1×10^{-9} second.

As the charge on the drops is reduced, a progressively smaller fraction of the pairs of coalescing drops discharges by spark, as indicated by a characteristic signal on a photomultiplier or on the oscilloscope used to determine Δp. Curves *a* and *b* of Fig. 1 show, respectively, the charges required for 80 percent and 20 percent of the collisions between charged drops to be preceded by a spark; the other curves (Fig. 1) help to put the observed threshold charges into physical context.

Observations of UHF radio emission from warm clouds, with narrow-band receivers, have been reported (*3*). The pulses are too strong to have been produced by discharges between single pairs of drops. However, if many pairs were triggered simultaneously (within 10^{-3} second, the time constant of the receiver system), pulses of the observed amplitude might be generated by some mechanism not yet understood but possibly akin to that shown in the cover photograph.

Theory of Radiation

The low-frequency limiting form of the spectral intensity of the energy radiated from a swarm of drops dis-

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charging in pairs at random times is directly proportional to the square of the frequency. Thermal radio energy has the Rayleigh-Jeans square-law dependence on frequency. Thus, an apparent temperature T*, applicable over a range of frequencies, may be assigned to a swarm because of the drop-to-drop discharges occurring in it. A discussion of this radiation by Atkinson and Paluch (*4*) may be applied to a swarm for which all orientations of colliding pairs are equally likely. The result is

$$T^* = 4.58 \times 10^{24} \ (\Delta p)^2 N_s \qquad (1)$$

where N_s is the number of discharges per second occurring per square-meter column lying along the observation path, and Δp is the associated change, per discharge, of the dipole moment in coulomb-meters.

The low-frequency limit (Eq. 1) is valid up to a frequency that approximately equals the reciprocal of 2τ, the duration of the spark. The frequencies at which Eq. 1 is a good approximation may be as high as 30 gigahertz (1 centimeter) in the case of discharging water drops. Our remaining discussion will be based on the assumption that 2τ is short enough for Eq. 1 to be a valid approximation. Uncharged drops or drops having charges below the threshold shown in Fig. 1 can spark and radiate in a similar manner if they collide in sufficiently large electric fields, with considerable addition to N_s; this process is not considered in this article.

A cloud may radiate true thermal energy at UHF and microwave frequencies, tending to obscure the determination of T^*. Fortunately, in the radio range a cloud is not a black-body radiator, and the equivalent temperature of this thermal energy is considerably less than the thermodynamic cloud temperature of possibly 220° to 300°K.

Application to Thunderstorms

Gunn (*5*) measured the charges on raindrops as a function of altitude inside active thunderstorms: over a considerable depth of the atmosphere, the average charge exceeds the threshold (Fig. 1) required for discharge between oppositely charged drops. Gunn also reports the average mass and concentration of the drops carrying these charges; from this information one can estimate the number of collisions between oppositely charged particles and, from Eq. 1 for a change in dipole moment (Δp, 2×10^{-14} coulomb-meter), compute an equivalent noise temperature for a cloud to determine whether this type of noise should be detectable with radiometers above the general thermal and cosmic-noise background.

Table 1. Data (*5*) on thunderstorm raindrops and their charges.

Size category	Conc. (m^{-3})	Radius (mm)	Terminal veloc. (m/sec)	Av. charge ($\times 10^{-10}$ coulomb)
Larger	142	0.8	6	± 0.67
Smaller	142	.6	5	± .67

Consider a volume of length L and unit area, in a cloud containing N_i drops per unit volume of radius r_i, having terminal velocity W_i and $\pm q$ units of charge per drop, with a uniform vertical electrical field. The number of collisions, N_c, per second between oppositely charged drops in this volume is given by

$$N_c = \frac{\pi L}{2} \sum_{j \geqslant i} N_i N_j (r_i + r_j)^2 \, | W_j - W_i | \, \epsilon_{ij} \qquad (2)$$

where half the drops in each size category are assumed to be negatively charged, half are positively charged, and ϵ_{ij} is the efficiency of collision between oppositely charged drops belonging to the ith and jth categories. If the trajectories of the drops were straight lines, ϵ_{ij} would be 1. In general, when oppositely charged drops and electric fields are present, ϵ_{ij} is greater than 1 and depends on the magnitude of the charge, field strength, and drop size; numerical integration is required for its determination. Estimates of the temperature T^* obtained by using $\epsilon_{ij} = 1$ are of interest because they provide lower bounds to the quasithermal temperature T^*, and because they can be used conveniently as a basis for evaluation of results of more complex computations.

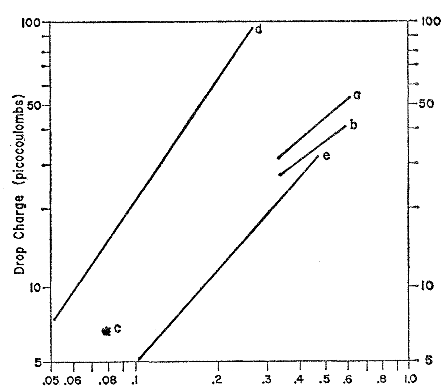

Fig. 1. Threshold charges required for spark discharge. (*a*) Experimentally observed charge required for 80 percent of drop pairs to discharge by spark; (*b*) experimentally observed charge required for 20 percent of drop pairs to discharge by spark; (*c*) smallest-radius drops studied in laboratory; (*d*) upper limit to charge, according to criterion for hydrodynamic stability; (*e*) sparking charges computed from data (*11*) on sparking potentials.

The sizes, charges, and concentrations used in an evaluation of Eq. 2 for $\epsilon_{ij} = 1$ are shown in Table 1; they are derived from Gunn's data. Applying these data to a thunderstorm core and taking L to be 10^3 meters, we obtain $N_c = 60$. Because the average charge is close to the experimentally determined threshold charge, we assume that for each polarity half the drops exceed the threshold and half fall below, giving $N_s = (\frac{1}{2} \times \frac{1}{2}) N_c = 15$. By use of $\Delta p = 2 \times 10^{-14}$ coulomb-meter, $T^* = 0.027$°K, a value too low for detection by radiometer techniques. However, the concentrations of particles derived from Gunn's data are considerably lower on the average than the maximum concentrations of particles inside thunderstorms given by Jones (*6*). Jones's data (*7*) give drop concentrations in thunderstorms, for drops of the radii listed by Gunn, exceeding Gunn's by an order of magnitude.

If concentrations greater by an order of magnitude than Gunn's are used, T^* becomes greater by two orders of magnitude—2.7°K. This apparent temperature should be detectable by radiometer techniques if suitable frequencies are used. If one assumes that $\epsilon_{ij} = 1$, the trajectories are straight lines, and the assumption implicit in Eq. 1, that all orientations of the drops at contact are equally likely, does not hold. The radiation is partially polarized, so that the effective temperature of an antenna, sensitive to the vertical component of the electrical field, would be twice as large as the effective temperature of an antenna sensitive to the horizontal component, and T^* would vary between 2° and 4°K, depending on orientation of the antenna.

Computations from Eq. 2 were modified by changed values (due to electrical forces) for the relative velocity

$(W_j - W_i)$ and the collision efficiency ϵ. These modifications were evaluated for a more complex distribution consisting of 20 positively charged and 20 negatively charged, equally populated species of drops, equally spaced in 20-micron-radius steps from 0.5 to 0.9 millimeter. Half the drops carried $+ 0.67 \times 10^{-10}$ coulomb; the other half, $- 0.67 \times 10^{-10}$ coulomb. The total number of drops per cubic meter was 2840, greater by an order of magnitude than the value listed in Table 1 but compatible with Jones's data. The computation of collision efficiency took account of the effect of the gravitational field, charge on the drops, a vertical electrical field varying from zero to 10^6 volts per meter, and the aerodynamic drag that each drop would experience in the absence of the other. The computation of the relative velocity $(W_j - W_i)$ took into account electrical, gravitational, and drag forces. For a given pair of drops, an imposed electrical field increased or decreased the factor of relative velocity, depending on whether it aided or opposed the action of the gravitational field. Low relative velocities favored long interaction times and high collision efficiencies. Evaluation of Eq. 1 for T^* (again N_s was taken to equal $N_c/4$) gave a temperature of 22.5°K at $E = 0$, a minimum temperature of 15.1°K at $E = 5 \times 10^4$ volts per meter, and a temperature of 78°K at $E = 3.5 \times 10^5$ volts per meter. If electrical fields and charges do not destroy the previously mentioned collision anisotropy that exists when the trajectories follow straight-line paths, estimates for T^* may range up to 117°K.

Measurements of free charges in thunderstorms are difficult to make. If charges of the magnitude reported by Gunn (*5*) do appear in thunderstorm cores and if drop concentrations are compatible with Jones's data, the above calculations show that the charges should be detectable with suitable radiometers. One could then check the magnitude of drop charges by measuring the apparent temperature T^* without physically disturbing the cloud or intercepting the drops. Knowledge of the charges on drops is vital to understanding of the mechanism responsible for the production of thunderstorm electricity and the growth of precipitation in a highly electrified environment. Antennas of short-wavelength radiometers can be highly directional, permitting more detailed study of portions of a storm as a function of time.

These studies of the quasithermal radio emission from discharging drops may be of interest in discussion of the temperature of Venus (*8, 9*). The observed planet-wide cloud cover and suggestions (*10*) to the effect that the clouds are continuously precipitating, taken together with the universally observed ease with which aerosols become charged, help to make plausible the suggestion that a portion of the microwave temperature originates as discharges involving vast numbers of charged particles; particles with lesser charge, colliding in strong electric fields, could provide considerable additional radiation. Atkinson and Paluch (*4*) estimate that 1.4×10^6 discharges per square meter are adequate to explain all the Venusian temperature of approximately 650°K.

Summary

Electric discharges between free-falling drops have been observed and studied quantitatively in the laboratory. These data and information from terrestrial thunderstorms suggest that augmentation of the UHF temperature of thunderstorms by discharges could amount to 117°K. If similar discharges occurred in the atmosphere or on the surface (or in both regions) of Venus, 1.4×10^6 discharges per second per square meter would be required to produce the microwave temperature observed (approximately 650°K). It is not probable that such radiation supplies the whole microwave temperature observed; some fraction must be true thermal radiation as described by Plummer and Strong (*9*), in which case the probable number of required discharges is reduced accordingly.

References and Notes

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