vertical distribution of air temperature. In some cases the raindrops are supposed to have been formed in the warm upper current of air and to have fallen to the earth's surface where air temperature is below the freezing point. In the other cases this phenomenon may be explained by assuming that the raindrops have been formed in the ascending current of air highly supersaturated with aqueous vapor. From thermodynamical considerations the author has shown that when the condensation takes place continuously in the highly supersaturated air, both snow crystals and raindrops are formed even though the air temperature is many degrees below the freezing point.—*T. O[kada]*.

## NEWTONIAN CONSTANT OF GRAVITATION AS AFFECTED BY TEMPERATURE.[1]

By P. E. SHAW.

*[Reprinted from* Science Abstracts, Sect. A, Aug. 25, 1916, §860.]

This paper deals with the possible existence of a temperature coefficient in the law of gravitation and gives an account of experiments made to discover this coefficient. The apparatus used is of the Cavendish torsion-balance type, and the range of temperatures was from 15° to 250°C. The investigation has extended over a number of years and was carried out in a vault of the physics department of University College, Nottingham. It yields evidence for a positive temperature effect of gravitation and measures its value.

The accumulation of negative results in the experimental study of gravitation is remarkable. In consequence of the indifference of the gravitative force to changes of conditions (other than those given by the simple law $f = GMmd^2$), none of the many theories of gravitation so far propounded has received general acceptance for lack of data wherewith to test them. Some recent theories which consider the possibility of temperature effect are the following: N. Morazov (1908) advanced a wave theory in which the attraction of masses would vary with temperature; G. Mie (1913) gave a theory of matter which includes among its corollaries a temperature coefficient of $10^{-13}$ per degree C. to the so-called Newtonian constant; N. Bohr (1913), in a paper on the constitution of the atom, assumed that gravitation like radioactivity is unaffected by all physical and chemical agencies.

Previous determinations of the Newtonian constant have been made at ordinary temperatures only, special care being taken to maintain uniformity in temperature throughout the apparatus used; otherwise convection in the air or strains in the movable system might produce grave errors. This is shown repeatedly in the well-known researches by C. V. Boys and J. H. Poynting. The necessity of providing a steady temperature about the delicate parts of the apparatus has previously been considered an insuperable bar to any direct experiment to discover a temperature effect for G. Yet indirect investigations have been made. Poynting and Phillips (1905) counterpoised a mass of 208 gm. on a balance and varied its temperature between 100° and −186°C. They came to the conclusion that the resulting change in weight, if any, was less than $10^{-9}$ per degree C. for the range 100° to 0°C., and $10^{-10}$ per degree C. for the range 0° to −186°C.

Another balance experiment on change in weight with temperature by Southerns (1906) led to a somewhat similar result.

In looking for a method to continue and extend these researches it is observed that a weight of say, 1 gm., can be determined on a balance to $10^{-8}$ under favorable conditions, whereas in a gravitation apparatus, like that of C. V. Boys, the attraction of one mass on another can not be found with greater accuracy than $10^{-5}$ at the utmost. Thus, apart from other reasons, it would be futile on the latter type of apparatus to look for a temperature effect between 100°C. and −186°C. on the small mass, *m*, since the above negative results have established the case with the greatest possible accuracy. But, in these balance experiments of Poynting and Phillips, the large mass M (in their case the earth) was unchanged in temperature. Now M is incomparably larger than *m* and might have a preponderating influence, whereby change of *its temperature alone* would affect the mutual attraction. In the work referred to, Poynting and Phillips suggested (though without any a priori grounds) the feasibility of some such expression as the following:

$$f = G\left[1 + K\frac{Mt + mt'}{M + m}\right]\frac{Mm}{d^2}, \qquad (1)$$

where K is a temperature coefficient and $t$, $t'$ are increments in temperatures of M and *m*. When M/*m* is very great, this reduces to

$$f = G(1 + Kt)(Mm/d^2) \qquad (2)$$

so that, on the above supposition, the mutual attraction would be influenced by change in temperature of the large mass only.

Admitting the possibility involved in (2), weight experiments must be abandoned in the endeavor to detect a temperature effect in gravitation and an apparatus adopted, having both masses (M and *m*) under control as regards temperature.

It is supposed by some that Kepler's third law establishes the constancy of G. But the present author has tried to show[2] that this is false, and that the common practice of obtaining the masses and densities of heavenly bodies (sun, earth, planets, etc.) by assuming the invariability of G is at fault. It was there held that in such a view Kepler's laws are strained beyond their legitimate use.

A survey of previous researches on gravitation is then given and affords some slight information as to temperature effect; five cases are noticed.

In this connection it may be noticed that there are three classes of work, the results from which should be distinguished: (1) Change in temperature of both M and *m* (*indirectly* by Boys, Baily, von Sterneck); (2) Change in temperature of M only (*indirectly* by Mendenhall, *directly* in the present research); (3) Change in temperature of *m* only (*directly* by Poynting & Phillips).

In the present research a number of early experiments were made in a variety of ways. Finally, a form was adopted closely resembling the Cavendish experiments of Boys; that is to say, the small masses, *m*, *m*, were hung at different heights inside an exhausted chamber and were attracted by the large masses, M, M, hung at corresponding heights, but outside the chamber. The small masses were of silver, the large ones of lead. The

[1] Phil. trans., Royal soc., London, May 27, 1916, 216: 349-392.

[2] *See* Science Abstracts, 1915, § 1628.

latter were electrically heated, their temperatures being read by mercury thermometers. The zero positions of the small suspended system were deduced by noting the turning points as read by a distant telescope and scale. Thus the relative gravitative effects with the large masses cold and hot are found by observing the shift in each case on rotating the large masses from the one attracting position to the other.

Elaborate precautions were taken to avoid various disturbances or spurious effects. Those dealt with are electrostatic, magnetic convection, radiometer pressure, occluded gases, damping, radiation pressure, conduction of heat, and displacements of apparatus. Taking all circumstances into consideration, a pressure of 14 mm. was held to be most satisfactory and was adopted in many of the later experiments. The results of the experiments with the final form of apparatus are summarized in the table [not reproduced here]. From this it is deduced, for the given temperature range of the larger masses (of about 47 kg. each) if a linear relation be assumed, that

$$f = G(1 + a\theta)Mm/d^2,$$

where $a$ is a temperature coefficient of value $(+1.20 \pm 0.05) \times 10^{-5}$ per degree C.—*E. H. B*[*arton*].

## GRAVITATION AND TEMPERATURE.[3]

By J. L[ARMOR].

[*Reprinted from* Science Abstracts, Sect. A, Aug. 25, 1916, §861.]

As the outcome of a very delicate systematic series of experiments, it is announced by P. E. Shaw [see above] that when one large mass attracts a small one the gravitative force between them increases by about 1/500 as the temperature of the large mass rises from, say, 15° to 215°C.; that is, it increases by about $1.2 \times 10^{-5}$ of itself per degree C. This seems to be a very startling result, at any rate if temperature is merely the expression of internal molecular motions, as indeed the experimenter seemed to admit.

By Newton's principle gravitation between masses must act reciprocally; the result, therefore, means that the astronomical mass of a body must increase with temperature by $1.2 \times 10^{-5}$ of itself per degree C.

The pendulum experiments of Bessel and recent determinations by Eötvös seem to establish proportionality between gravitational mass and mass of inertia, irrespective of temperature, well beyond these limits. Thus inertia also would have to increase with temperature, and when a freely moving mass is becoming warmer its velocity must be diminishing, for its momentum must be conserved. A comet like Halley's is heated upon approach to the sun; thus it should suffer retardation in the approaching, and acceleration in the receding part of the orbit, enough, probably, to upset existing astronomical verifications.

Electrodynamic theory does establish unequivocally an increase of inertia of a body arising from gain (SE) of thermal or electric energy; but this is only of amount $SE/c^2$, where $c$ is the velocity of radiation, and so is minute beyond detection. The question whether there is also an equivalent increase in gravitational mass evades discussion until some link connecting gravitative and electric forces has been established.—*E. H. B*[*arton*].

[3] Review in Nature, London, June 15, 1916, 97:321, of the paper by P. E. Shaw abstracted above.

## ICE CRYSTALLIZATIONS FROM AQUEOUS SOLUTIONS.[1]

By R. HARTMANN.

[*Reprinted from* Science Abstracts, Sect. A, May 25, 1916, §628.]

The solutions contain cane sugar, glycerol, alcohol, NaBr, $MnSO_4$, NaOH, $FeCl_3$, or HCl, etc., in water, and are undercooled, with the two last-mentioned solvents to −38° and −40°C. The crystallites then separating are of four or five types: (a) The skeletons or nuclei are hexagonal or rectangular in outline, but the three or two (rectangle) axes cross in both cases at 60; (b) and (c) spherulites, radial or built up of plates; (d) feathery growths. With moderate undercooling (a) is obtained; (b) and (c) with heavy undercooling; (d) in very dilute solutions, whatever the cooling. In order to see whether the nuclei have all the same melting points, they were placed in water at −2° and then very slowly heated up, differences of 0.001 degree C. being observable; the melting points were always found normal. In the case of the two (a) types, the linear velocity of crystallization was further determined; no differences were observed. When, in the spontaneous crystallization, a nucleus happens to settle on the glass surface with its base, a hexagon seems to be formed; when with its triangular edge a rectangle is formed.—*H. B*[*orns*].

## THE KATA THERMOMETER AS A MEASURE OF THE EFFECT OF ATMOSPHERIC CONDITIONS ON BODILY COMFORT.[2]

By C.-E. A. WINSLOW.

[*Reprinted from* Science Abstracts, Sect. A, Aug. 25, 1916, § 862.]

The readings of an ordinary thermometer afford a poor indication of the degree of comfort felt by the average individual, who in addition to feeling the effects of temperature is also sensitive to air movements. To obtain a more satisfactory measure of comfort L. Hill devised the kata-thermometer outfit, which consists of two thermometers with large bulbs and stems graduated from 86° to 110°F., one to be read as a dry- and the other as a wet-bulb thermometer. The bulbs are heated to about 110°F., and then, while they are freely exposed, the time taken to fall from 100° to 90°F. is noted. The author has taken three series of readings with the apparatus under different circumstances. At the same time a band of observers estimated the degree of comfort of the conditions on an arbitrary scale of 1 to 5, in which 3 represented ideal conditions and 1 and 5 extremes of cold and warmth, respectively. The comparative instrumental and personal results are set out in tables and on a diagram. As a result it seems clear that the instrument is of great value in measuring the actual influence of air conditions on the body and is greatly superior to the ordinary thermometer for this purpose. The curves show that conditions of maximum comfort are represented by falling times, from 100° to 90° F., of 45–60 seconds for the wet-bulb, and 150–180 seconds for the dry-bulb.—*J. S. Di*[*nes*].

## BALL LIGHTNING ON PUY DE DÔME.[3]

By E. MATHIAS.

[*Reprinted from* Science Abstracts, Sect. A, Aug. 25, 1916, § 917.]

On April 15, 1916, the phenomenon of ball lightning was observed on three occasions—at $18^h\ 20^m$, $18^h\ 30^m$, and $18^h\ 50^m$—taking the form of a brilliant fireball with somewhat hazy contour, afterwards changing to an oval

[1] Zeitsch. f. Anorg. Chem., Aug. 6, 1914, 88:128–132.
[2] Science, New York, May 19, 1916 (N. S.), 43:716–719.
[3] Comptes rendus, Paris, Apr. 25, 1916, 162:642.