III. "On Effects of Retentiveness in the Magnetisation of Iron and Steel. (Preliminary Notice.)" By J. A. Ewing, B.Sc., F.R.S.E., Professor of Mechanical Engineering in the University of Tokio. Communicated by Professor Sir William Thomson, F.R.S. Received May 6, 1882.

The term Hysteresis was introduced in a paper,* recently communicated to the Royal Society, to designate a peculiar action which was observed in the inquiry then recorded, and which had also presented itself in an earlier investigation—of the effects of stress on thermoelectric quality.† It was found that when a stretched iron wire was gradually loaded and unloaded the changes of thermoelectric quality lagged behind the changes of stress, so that curves exhibiting the relation of stress to thermoelectric quality during the putting on and taking off of the load were far from coincident, but inclosed between them a wide area.‡

In prosecuting those experiments it occurred to me that there is much room for investigation of hysteresis§ in the changes of magnetisation of iron and other substances produced by (1) change of the magnetic field; (2) change of stress; (3) change of temperature. In (2) and (3) two cases are to be considered:—First, when the substance is exposed to a constant magnetising force; second, when the magnetisation which is changed is wholly residual.

From the known character of residual magnetism we may at once infer that when magnetisation along any axis is changed so considerably that its sign is reversed there must be hysteresis, but it is not clear that any such phenomenon need appear when the action is confined to one sign. In fact, Maxwell's extension of Weber's theory of induced magnetism|| assumes that residual magnetism resembles the "permanent set" of a strained solid, and implies that any subsequent application of a magnetising force in the same direction with and not exceeding that by which the residual magnetism has been produced, will give changes of a quasi-elastic character not exhibiting the action which I have called hysteresis.

By the direct magnetometric method, and also by the ballistic

* "On the Production of Transient Electric Currents in Iron and Steel Conductors by Twisting them when Magnetised, or by Magnetising them when Twisted." "Proc. Roy. Soc.," vol. 33, p. 21.

† "Effects of Stress on the Thermoelectric Quality of Metals. Part I." "Proc. Roy. Soc.," vol. 32, p. 399.

‡ Since the paper cited was laid before the Royal Society, I have learnt that M. Emil Cohn has anticipated me in the discovery of this peculiar feature of the effects of stress on thermoelectric quality. ("Pogg. Ann.," N.F., VI, 385.)

§ Or effects of retentiveness—Note by Sir William Thomson, May 5, 1882.

|| "Treatise on Electricity and Magnetism," II, chapter vi.

method (as used by Rowland and others), I have examined at great length the changes of magnetisation which occur in iron and steel when the magnetising force is progressively increased, diminished, again increased, reversed, and so on. The results show in the most conclusive manner that all changes of magnetisation produced by slow or fast, continuous or discontinuous, changes of the magnetising force exhibit hysteresis. If we carry the metal through any cycle of magnetisation, the curves giving the relation of I (the intensity of magnetisation) to H (the magnetising force) form loops, and it does not appear that the loops are different in any essential respect (except size) when the action is confined to one sign from the loops given when the sign of the magnetisation is reversed.

The remarkable feature of the curves is, that when the magnetisation of iron is conducted in such a manner as to be uniform throughout the piece experimented on, the initial change which occurs when we pass from increase to decrease of the magnetising force, or *vice versâ*, is indefinitely small relatively to the initial change of the force. In other words, say that we stop decreasing H and begin to increase it, then $\frac{dI}{dH}$ is at first zero.

The difference between the curves for increase and decrease of the magnetic force is of a perfectly static character. If it is to be explained by internal friction, the friction is analogous to that of solids, and does not at all resemble the viscosity of liquids. The phenomenon here described is independent of the quasi-viscous resistance to changes of magnetisation which is due partly to the induction of currents in neighbouring conductors, including the magnet itself, and partly to the thermomagnetic properties of the metal discussed by Sir W. Thomson ("Phil. Mag.," vol. v, 1878, pp. 24–25). The influence of those causes disappears when the changes of magnetisation take place very slowly, or when a sufficient interval of time is left after each change of magnetic force before a reading of the magnetisation is taken.

When any cyclic change of I is made to take place by varying H cyclically, the area of the loop so formed, or $\int I dH$, is not only proportional to, but actually the measure of the work done on the magnet, per unit of volume, in performing the cycle. In cases where changes of the magnetisation take place very slowly this is wholly spent on the magnet itself, and its equivalent is, no doubt, to be found in the heating effect of the cycle. When, however, the changes of magnetisation take place at a finite rate, this area must of necessity be greater, since the work done in performing the cycle is then greater for two reasons; first, because of the energy expended in inducing currents in neighbouring conductors; and, second, because of the dissipation of energy involved in the heating and cooling effects

which Thomson has shown must occur on account of the fact that the susceptibility to magnetic induction is a function of the temperature.

I have endeavoured to account for the static hysteresis by supposing that the rotation of Weber's magnetic molecules is opposed by a frictional couple of constant moment, not necessarily the same for all the molecules in a given piece. It seems not unlikely that residual magnetism itself may be due to this frictional sticking of the molecules rather than to the quasi-plasticity suggested by Maxwell. The examination of this theory, as well as the description of the experiments, some of whose results have been briefly mentioned in this notice, will form the subject of a more detailed communication.

Another portion of the work has consisted in looking for hysteresis in the changes of the longitudinal magnetism of iron wires, produced by pulling and relaxing pull, the wires being under the influence of the vertical component of the earth's magnetic force, which in Tokio is about 0·34 C.G.S. unit. Sir W. Thomson* has investigated very extensively the general effects of stress on the magnetisation of iron and other metals, in magnetic fields of various strengths, but without special reference to this point. Only in the case of torsion (alternately to opposite sides) is mention made of any action of the kind which I have termed hysteresis. His researches were for the most part conducted by the ballistic method,† by which the currents induced in a solenoid surrounding the wire were observed when a single

* "Electrodynamic Qualities of Metals," "Phil. Trans.," 1856, 1876, 1879.

† [Note by Sir William Thomson of May 3, 1882.—This is not quite so. The experiments described in §§ 214—244 of my "Electrodynamic Qualities of Metals," Part VII ("Phil. Trans." for 1879, p. 55), were performed by the magnetometric method. My earlier experiments described in §§ 178—213 ("Phil. Trans." for 1876, p. 693, and for 1879) were performed by the ballistic method.

The following is taken from a preliminary statement (§ 178) :—"Early in the year 1874, I made arrangements to experiment on the magnetisation of iron and steel wires in two different ways—one by observing the deflections of a suspended magnetic needle produced by the magnetisation to be tested, the other by observing the throw of a galvanometer needle, due to the momentary current, induced by each sudden change of magnetism. The second method, which for brevity I shall call the ballistic method, was invented by Weber, and has been used with excellent effect by Thalén, Roland, and others. It has great advantages in respect of convenience, and the care with which accurate results may be obtained by it; but it is not adapted to show slow changes of magnetism, and is therefore not fit for certain important parts of the investigation. On this account I am continuing arrangements for carrying out the first method, although hitherto I have obtained no good results by it."

The first method was accordingly followed in all the latter part of my experiments on this subject; not only those described in §§ 214—244 referred to above, but also in further investigations which I have continued up to the present time, and of which I hope to offer results to the Royal Society before long.]

weight was put on and taken off. By making several steps, instead of only one, in the application and removal of the load, the existence of hysteresis may easily be demonstrated by this method; but I have preferred the direct magnetometric method, which has the immense advantage of exhibiting the actual magnetic state of the stretched wire at any time.

Each wire was hung vertically with its upper end on a level with a mirror magnetometer. It was then annealed by heating to bright redness with a spirit-lamp, and after it had become cool, weights were progressively applied.

During the earliest part of the first loading certain very interesting apparently anomalous effects occur, which will be described in the detailed account. Apart from these, which are easily distinguished, the following is the normal action:—

If to the annealed wire any load not exceeding the elastic limit is successively applied and removed (without shock), its application causes a *decrease* and its removal an *increase* of magnetisation. The "on" and "off" curves of stress and magnetism are widely different, and afford an excellent instance of hysteresis.

Next, let the wire be stretched beyond its limit of elasticity. The stretching is accompanied by a decrease of magnetisation, which continues so long as the wire keeps "running down." When the load is removed it is found that a great diminution of magnetisation has taken place; but besides this, the wire has undergone a very remarkable change with respect to its subsequent behaviour under stress.

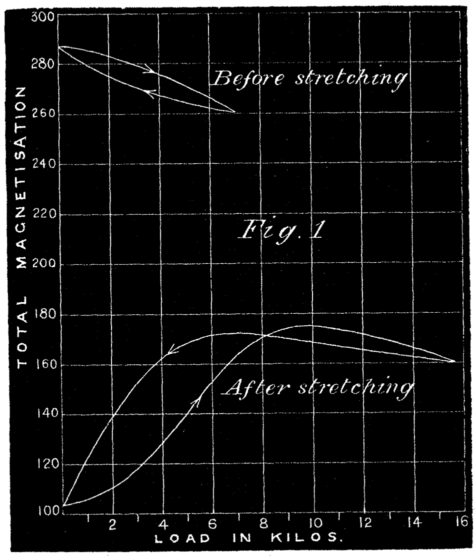
For let weights now be gradually applied: they cause at first an *increase** of magnetisation, but this passes a maximum and falls off slightly as that value of the load is approached which previously was applied to produce the permanent set. Let the load then be gradually removed: the magnetisation at first increases, passes a maximum (at a considerably lower value of the load than that which gave the maximum during application), and finally diminishes rapidly to its previous value with no load.

These effects will be clearly seen by reference to fig. 1, which shows the results of a small part of one set of observations. The ordinates are proportional to the total magnetisation, and the abscissæ are the loads in kilogrammes. In this case the wire was of moderately soft iron, 0·79 millim. in diameter, and had a well-defined limit of elasticity at about 10 kilos.

The upper part of the diagram shows the effect of gradually apply-

* This agrees with Sir W. Thomson's observation that with low magnetising forces the effect of "on" is to increase, and "off" to diminish magnetism. The description of the wire examined by him shows that it was in fact in the state described in the text. (See "Phil. Trans.," 1879, p. 56.)

ing and removing 7 kilos. before the wire had been stretched at all by any greater load. The lower part shows the effect of applying and removing weights nearly equal in all to 16 kilos. after the wire had been previously stretched by the same load. The initial magnetism for zero stress had then fallen to 104, but during application it rose to 174 with 10 kilos., and again during removal it rose to 172 with $6\frac{1}{2}$ kilos.

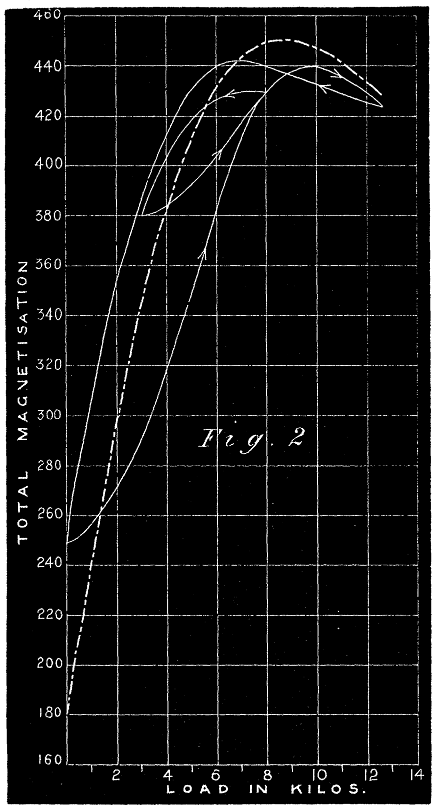


The series of experiments from which this figure is taken shows that the maximums of magnetisation during loading and unloading (when conducted without shaking the wire) appear only after some permanent set has been given, and that they gradually shift out to the right as the amount of permanent set is progressively increased.

A number of other iron wires tested in the same way agree with this one in giving *decrease* of magnetism for "on," and *increase* for "off" before stretching beyond their limits of elasticity, and afterwards *increase* for "on" and *decrease* for "off." It appears that (at least when the strain has occurred in the circumstances in which it occurs here) this difference of behaviour forms an unfailing criterion by which we may distinguish a piece which has received permanent set from a piece in the annealed state.

A careful examination of the initial parts of the curves which are formed when after loading we change (without mechanical disturbance) to unloading, or *vice versâ*, has brought out the fact that, calling I the magnetisation and p the stress, $\frac{dI}{dp}$ is always initially

zero. The *magnetic rigidity*, as the reciprocal of this differential coefficient might be called, is infinite at the beginning of any change from loading to unloading, or from unloading to loading, provided that the change takes place without agitation of the wire. In the thermoelectric experiments described in my former paper, the beginning of the new curve generally continued to show the same kind of change as had been going on before. The same peculiarity can be reproduced here if the loading or unloading occurs with a slight vibration of the wire, and I now think it almost certain that its presence in the thermoelectric curves was due to a very small amount of mechanical disturbance which accompanied the changes of load.



When the wire is vigorously tapped during the loading and unloading, the "on" and "off" curves so nearly approach coincidence as to lead to the conclusion that a sufficient amount of vibration would destroy the hysteresis altogether. As an instance of this, the full lines in fig. 2 show the changes undergone by another wire (which

had been permanently stretched) when subjected to the cycle 0—8—3—12½—0 without vibration; while the broken line is the position in which the "on" and "off" curves very nearly coincided, when the same main cycle 0—12½—0 was passed through with the accompaniment of violent vibration. Its maximum lies, as regards load, between the two previous maximums, and the whole range of magnetic change is considerably increased.

The hysteresis which occurs in the relation of magnetisation to stress is absolutely static. The value of the magnetism associated with any condition (past and present) of stress is reached at once, and remains unchanged for any length of time, when the load is kept constant.

A full account of the experiments will be given when they are more complete. They are being conducted in the Laboratory of the University of Tokio, with the valuable help of the senior students of physics.

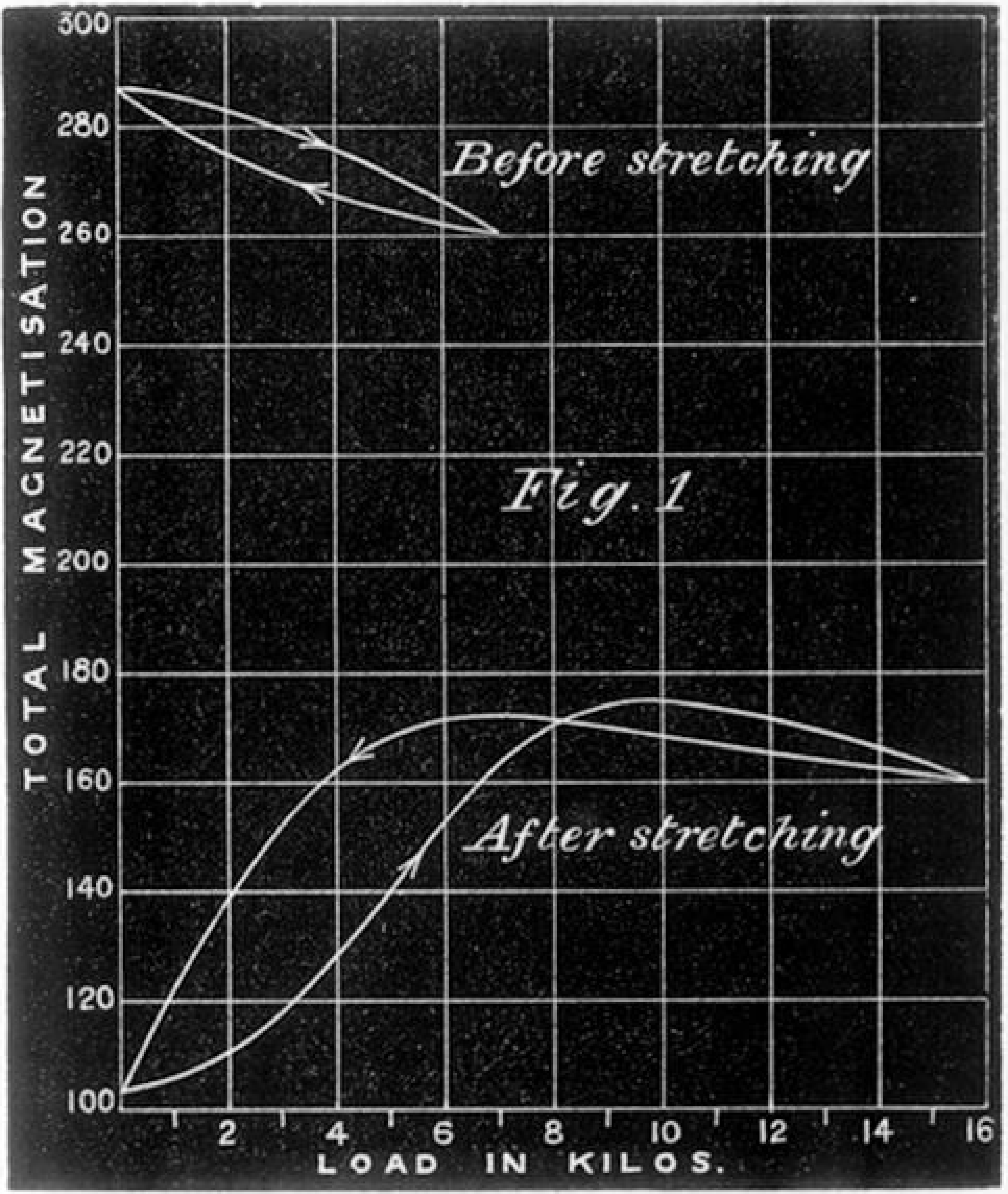
IV. "On Actinometrical Observations made in India at Mussooree in Autumn of 1880, and Summer and Autumn of 1881." By J. B. N. HENNESSEY, F.R.S., Deputy Superintendent Great Trigonometrical Survey of India. Received May 2, 1882.

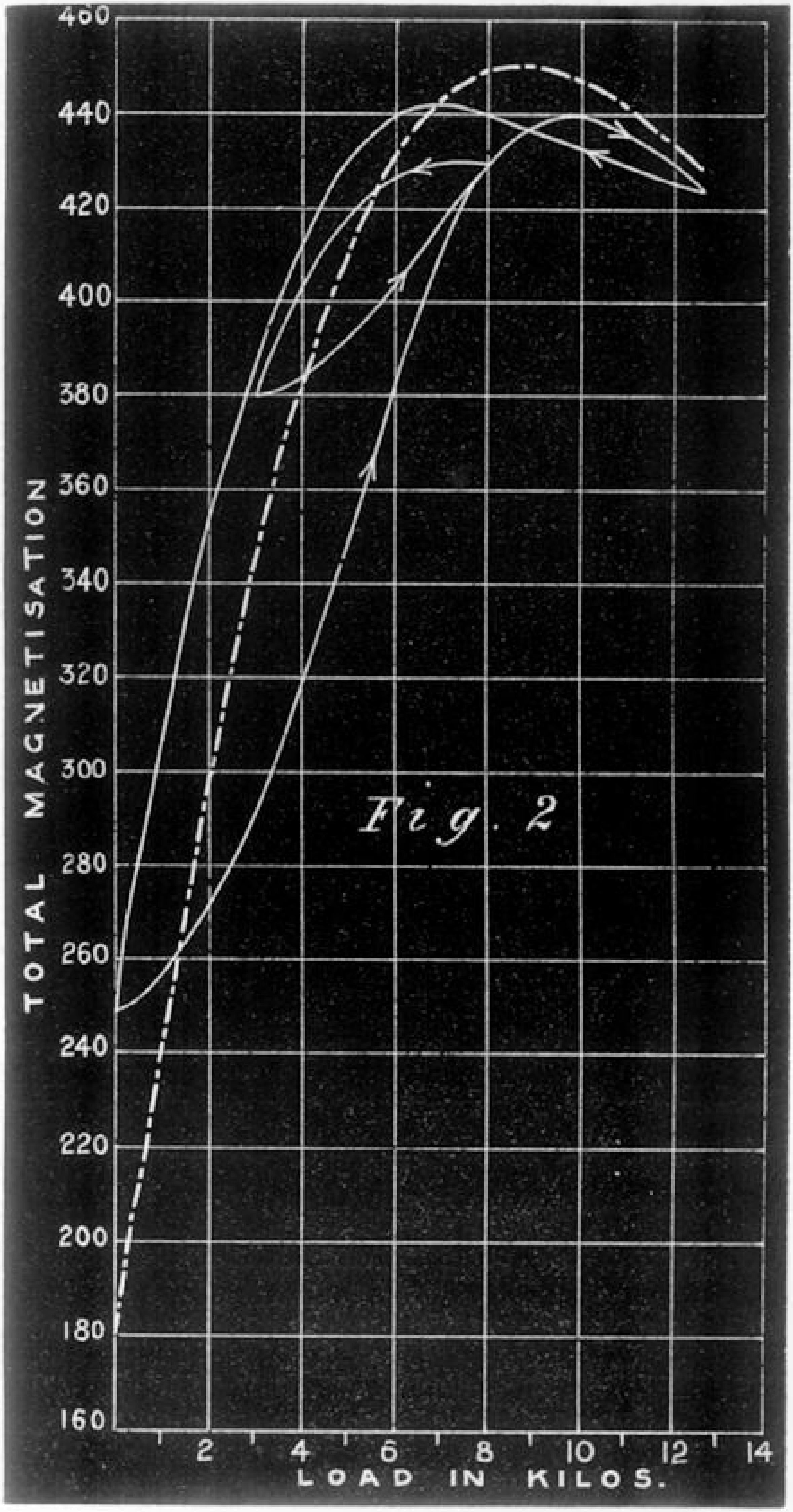
[PLATE 1.]

1. My last communication dealt with the actinometrical observations made by Mr. W. H. Cole, M.A., and myself in 1879; I have now the pleasure to submit the observations taken in 1880 by Mr. Cole, and in 1881 by Mr. H. W. Peychers* and myself. The former happen to be few in number, but the latter present the longest series I have ever been able to take, extending as they do over thirty-two days. The 1881 observations were moreover made under certain special conditions, which are not without interest. Hitherto the two actinometers used (belonging to the Royal Society) were both† of the kind invented by the Rev. G. C. Hodgkinson, and marked by me A and B. One of these was employed at Dehra, the other at Mussooree, the observations being taken as nearly as practicable at the same moments of time; but, as the former of these stations cannot be considered free from objections, which I have discussed in previous communications, I determined to restrict future observations to Mussooree alone. This

* This being the first occasion of mentioning Mr. Peychers' name, I add, that as he has worked under me for several years, I can vouch for him as an accurate and painstaking observer.

† Both these actinometers are still identical in all respects with their condition when received in 1868.


TOTAL MAGNETISATION
300
280
260
240
220
200
180
160
140
120
100
2
4
6
8
10
12
14
16
LOAD IN KILOS.
Before stretching
After stretching
Fig. 1



TOTAL MAGNETISATION
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
2
4
6
8
10
12
14
LOAD IN KILOS.
Fig. 2