PHYSICS

Determination of the Speed of Light

"A Classic of Science"

Foucault Invented the Standard Method of Measurement Used With Many Refinements by the Late A. A. Michelson

COMPTES RENDUS Hebdomadaires des Séances de l'Académie des Sciences, Tome 55, *Paris,* 1862.

Détermination expérimentale de la vitesse de la lumière; parallaxe du Soleil; (*Experimental determination of the speed of light; parallax of the sun*): *and*

Détermination expérimentale de la vitesse de la lumière; description des appareils; (*Experimental determination of the speed of light; description of the apparatus*);

By Leon Foucault. Translated for the Science News Letter by Helen M. Davis.

AT THE MEETING of May 6, 1850, I gave the result of a differential experiment upon the speed of light in two media of unequal densities; and at the same time I indicated that the same method, based upon the use of a revolving mirror, would serve to measure the absolute velocity of light through space.

When this project had been thoroughly discussed, the Director of the Observatory wished to hasten its performance and placed at my disposal the necessary resources. At the beginning of summer the apparatus was ready for use, but the bad weather did not allow me to begin as promptly as I should have wished the observations which required the presence of sunlight. But the sky finally cleared, and, profiting by these last beautiful days, I obtained results which seem to me to contain something pretty close to the expression of truth.

The actual apparatus did not differ essentially from that previously described except for the addition of a clockwork designed to move a circular screen toothed for the exact measurement of the speed of the mirror, and for the extension of the experimental line which, by means of multiple reflections, was carried from 4 to 20 meters. By thus increasing the length of the ray of light and applying more exactness to the measure of the time, I got determinations whose extreme variations do not exceed 1/100 and which, compared with their mean, give a series agreeing within 1/500.

As the result, the speed of light turns out to be notably diminished. Following the accepted values, this velocity would be 308 million meters per second, and the new experiment with the revolving mirror gives, in round numbers, 298 million.

We may, it seems to me, rely on the accuracy of this figure, in the sense that the corrections to which it is subject ought not to raise it more than 500,000 meters.

If we accept this new figure and combine it with the constant of aberation 20″.45 to deduce the parallax of the sun which is evidently a function of these two, we find, instead of 8″.57 the notably greater value of 8″.86. Thus the mean distance of the earth from the sun is diminished by about 1/30.

To give an idea of the degree of confidence which can be accorded to the series of observations used in this instance, I shall copy here a list of rough determinations chosen from those whose average agrees least with the general mean.

1024	1026
1025	1026
1029	1026
1028	1025
1027	1026
1026	1028
1027	1028
1025	1027
1026	1026.5
1027	1027

Mean 1026.47

This number 1026.47 agrees with an arbitrary length which belongs to the apparatus and which may be varied for each determination, in such a way as to produce a constant displacement of the image deflected by the revolving mirror.

In an early communication I promise to give a description of the apparatus sufficient to provide a basis for discussion and to acknowledge the ability and the services of the eminent workers who have been kind enough to assist me.

The Apparatus

In spite of limited space and lack of figures, I shall try to describe the main parts of the apparatus with which I obtained such a different value for the speed of light from that which has been current in science.

This apparatus is composed of:

A micrometric scale cut through the surface of a sheet of silvered glass;

A revolving mirror carried upon the axis of a little wind turbine;

A blower of constant pressure;

An achromatic objective;

A series of an odd number of concave spherical mirrors of silvered glass;

A mirror inclined for partial reflection;

A microscope for the micrometer,

And a circular screen in the form of a toothed wheel moved by clockwork.

I shall first describe the apparatus at rest.

A ray of sunlight reflected horizontally by a heliostat falls upon the micrometric scale which consists of a series of vertical lines 1/10 millimeter apart. This scale, which in the experiment is the real standard of measure, was ruled with much care by M. Froment. The rays which have passed through this original plane impinge at the distance of 1 meter upon the mirror rotating in a plane surface, where they undergo a first reflection which sends them back a distance of 4 meters to a first concave mirror. Between these two mirrors, and as close as possible to the plane mirror, is placed the objective,

Experiments by the same Foucault who measured light, laid the foundation for the invention of the

Gyroscopic Compass

by Sperry, who describes it in

THE NEXT CLASSIC INVENTION

having on one side the virtual image of the scale and on the other the concave mirror at its two conjugate foci. When these conditions are fulfilled, the ray of light, after passing through the objective, forms an image of the scale at the surface of the first concave mirror.

Hence the ray is reflected a second time in a direction sufficiently oblique to avoid the apparatus with the rotating mirror, of which it forms an image at a certain distance in space. At the place where this image appears is placed a second concave mirror, turned in such a way that the ray again reflected passes back near the first spherical mirror to form a second image of the scale; this is sent back by a third concave surface, and so on to the formation of a final image of the scale by a final odd-numbered concave mirror. I have been able to use up to five mirrors which develop a line 20 meters long.

The last of these mirrors, separated from the next-to-last, which faces it, by a distance of 4 meters, equal to its radius of curvature, sends the ray back exactly upon itself, a condition which is fulfilled accurately by superposing the returning image upon the outgoing one at the surface of the mirror opposite; this done, we can be certain that the ray reassembles the series, returns in its entirety by way of the plane mirror of the rotating apparatus and that finally all the rays appear on the scale, point by point, as they started out.

We can verify this return of the rays and procure an accessible image by turning aside by partial reflection at the surface of a mirror inclined at 45° a part of the ray which we can examine with a low-power microscope. This last, corresponding in every respect to the micrometric microscopes used in astronomical observations, forms with the scale and the inclined mirror a very stable combination.

In the apparatus thus described, the real image sent back to the microscope and formed the partially reflected return rays occupies a definite position with respect to the mirror and the scale itself. This position is precisely that of the virtual image of the scale seen by reflection in the plane of the mirror. At least it has that position when the apparatus is at rest. But when the plane mirror begins to turn, this image changes place, because during the time that the light took to traverse twice the broken line of concave mirrors, the rotating mirror continued to turn and the rays upon their return no longer find it at the same incidence as at the time of their arrival. As a result the image is displaced in the direction of motion of the mirror and this *deviation* increases with the speed of rotation; it evidently increases also with the length of the path and with the distance which separates the scale and the turning mirror. The way in which these various quantities are related in the experiment, hence the speed of light itself, is shown by a very simple formula which has been established and which I shall only quote here.

Calling V the velocity of light, n the number of revolutions per second of the mirror, l the length of the broken line included between the revolving mirror and the last concave mirror, r the distance from the scale to the revolving mirror and d the deviation observed, we find by inspection of the apparatus

$$V = \frac{8\pi nlr}{d},$$

an expression which gives the velocity of light in terms of quantities which it is possible to measure separately.

The distances l and r are measured directly with a rule or a strip of paper which can be compared with the unit of length. The deviation d can be observed micrometrically; but it remains to be shown how the number n of revolutions of the mirror per second can be determined.

Let us first explain how a constant velocity is impressed upon the mirror:

This mirror of silvered glass, which is 14 millimeters in diameter, is mounted directly upon the axis of a little air turbine of well-known design, admirably made by M. Froment. The air for it is furnished by a high pressure blower by M. Cavaillé-Coll, who has acquired a just reputation in building large organs. Since it is important that the pressure be very constant, upon leaving the blower the air passes through a regulator recently devised by M. Cavaillé in which the pressure does not vary more than 1/5 of a millimeter in a column of water 30 centimeters high. In flowing cut through the orifices of the turbine, the fluid thus represents a remarkably constant motive force. On the other hand, the mirror in accelerating soon meets resistance of the air about it which for a given velocity is also perfectly constant. The moving part held between these two contrary forces which tend to equilibrium cannot help but attain and keep a uniform velocity. Any obstruction to the outflow of the air moreover allows us to regulate this velocity within very narrow limits.

It remains finally to compute the number of revolutions or rather to impress upon the moving part a predetermined velocity. This problem has been completely solved in the following manner:

Between the microscope and the partially reflecting mirror is placed a circular disk, whose finely toothed edge infringes upon the image observed and intercepts a part of it; the disk turns uniformly upon itself, in such a way that if the image appears continuously, the teeth which it carries upon its circumference disappear from sight with the rapidity of the motion. But the image is not permanent, it results from a series of discontinuous appearances which are equal in number to the revolutions of the mirror, and in the particular case where the teeth of the screen also follow one another at the same rate, it produces to the eye an illusion easy to explain, which makes the teeth reappear as though the disk were not turning. Let us suppose then that the disk carrying n teeth on its circumference is making one turn per second and that at the same time we set the turbine in motion; if in regulating the outflow of the air motor we succeed in maintaining the apparent fixity of the teeth, we can know for certain that the mirror is really making n revolutions per second.

M. Froment, who made the turbine, has been kind enough to undertake to design and construct a clockwork to move the disk; this is a very remarkable piece of clockwork, which solves in an elegant way the problem of uniform motion in the particular case where there is no work to be done. Its success is so complete that every day I am able to start the mirror at 400 revolutions per second and to watch the two pieces of apparatus go in agreement of about 1/10,000 for whole minutes together.

Yet, in spite of having obtained such certainty on the side of measuring the time, I was surprised to find in my results discrepancies which were not in accord with the precision of the methods of measurement. After quite a long search, I finally found that the source of error was in the micrometer, which did not admit of nearly the degree of precision which we assumed for it. To meet this difficulty, I introduced into the system of observation a modification which finally resulted in a simple change of variable. Instead of measuring the deviation micrometrically, I adopt a value for this defined in advance, it shall be 7/10 of a millimeter or 7 whole divisions of the image, and I find by experiment what distance to establish between the scale and the revolving mirror to produce this deviation; the measurements have thus a length of about 1 meter, the lesser fractions still have a size visible directly and no longer allow room for error.

By this means the apparatus was cleared of the chief cause of uncertainty; since then the results have agreed within the limits of error of observation and the averages have been so constant that I am able to give with confidence the new value which it seems to me ought to represent something very close to the speed of light in space, namely: 298,000 kilometers per second of mean time.

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GENETICS

Dingo-Wolf Hybrid In Australian Zoo

SUCCESSFUL crossing between the dingo, wild dog of the Australian bush, and a male European wolf is reported in *Nature*. The litter of six pups, all female, was born in the zoological garden at Adelaide, Australia. One of the animals has been sent to Melbourne for hybridization experiments.

It is well known that dingo and domestic dogs can interbreed, but the present is apparently the first case on record of a cross with a wolf.

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GENERAL SCIENCE

Scientist Makes New List Of Extremes in Nature

THE BIGGEST elephant, the smallest germ, the shortest dwarf, the highest mountain, all the things of the universe to which can be applied the superlative "est," stir the human imagination.

Dr. B. S. Hopkins, University of Illinois professor who wrote his name into chemical history a few years ago by discovering the element illinium, has compiled in an article in the *Scientific Monthly* a list of the extremes of nature.

"Our natural curiosity which is stimulated by the use of the superlative degree is reenforced by the needs of our modern civilization," Dr. Hopkins observes. "A study of the extremes of nature soon passes far beyond the realm of mere curiosity and establishes itself as a means by which we can measure our progress in solving the problem of selecting the best material to serve our purpose in a certain specific application."

Some of nature's extremes include:

The heaviest substance known upon our earth is osmium, with a density which varies from 21.3 to 24.

The lightest substance known is hydrogen gas, unless there be considered highly evacuated X-ray tubes which contain streams of electrons which are fragments of disrupted hydrogen atoms.

The hardest material is the diamond.

The most ductile and malleable of our metals is gold.

The highest temperatures which have been sustained for a considerable time and measured with reasonable accuracy are in the neighborhood of 3500 to 3800 degrees Centigrade.

The most extreme cold that has ever been reached is the melting point of solid helium, 272.2 degrees Centigrade below zero which is within eight-tenths of a degree of absolute zero, that theoretical point where all heat vanishes.

The most costly substance known to commerce is radium which sells at a price that corresponds to more than two million dollars per troy ounce, making radium worth more than a hundred thousand times its weight in gold.

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more feet deep. Since the discharge of the electroscope in general is due to the cosmic rays and the radioactivity of the earth, the investigators feel that this location in and above non-radioactive water gives the best conditions under which to pursue their investigations.

Up to this time Dr. Millikan has obtained much evidence as to the nature of the cosmic ray by observing its effects through the eye piece on the electroscope. The newer apparatus contains a photographic film for permanently self-recording these effects. These records should render further repetition of these measurements unnecessary since any one interested will henceforth only need to come and measure up the films for himself, for these films will be completely free from the preconceptions as well as the errors of the individual observer.

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PLANT PATHOLOGY

Enzyme Theory of Virus Disease Upheld

EVIDENCE that the so-called "virus diseases" of plants and animals are caused by a non-living chemical substance that can attach itself to living matter, rather than by ultra-tiny living organisms, is claimed as the result of experiments on tobacco plants performed by Dr. Carl G. Vinson of the University of Missouri. Dr. Vinson's work apparently supports the belief, held on theoretical grounds by many physiologists and pathologists during the past thirty years, that the causes of these mysterious diseases of plants and animals are compounds analogous to enzymes, the digestive and respiratory "ferments" of normal organisms, but malefic rather than beneficent in their effects.

Frozen and Squeezed

Dr. Vinson's method of isolating the virus of tobacco mosaic was worked out during four years he spent at the Boyce Thompson Institute for Plant Research at Yonkers, N. Y., prior to coming to the University of Missouri. The first step was to freeze a quantity of