SCIENCE

VOL. 76 FRIDAY, NOVEMBER 25, 1932 No. 1978

SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. MCKEEN CATTELL and published every Friday by

THE SCIENCE PRESS

New York City: Grand Central Terminal

Lancaster, Pa. Garrison, N. Y.

Annual Subscription, $6.00 Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the Association may be secured from the office of the permanent secretary, in the Smithsonian Institution Building, Washington, D. C.

SPACE STRUCTURE AND MOTION

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INTRODUCTION

EVERYBODY is familiar with motion as an observed phenomenon. Motion, however, is not a simple thing, as we shall see in the following, and it has many aspects of extreme interest and far-reaching consequences. The most familiar kind of motion is that when I move my hand, for instance. This is a very complicated process involving human will, and most of our study must be confined to much simpler cases, although in the end we will include even such complicated motions in our picture. The simplest and most completely studied case is that of the motions of celestial bodies. Since we shall find that a study of these will give valuable clues for our interpretation of other motions, the writer will first give a description of these motions and of the properties of space which can be derived from them. We shall then find that these properties can be visualized by attributing to space a nearly uniform general structure. Close to atoms we shall also find that space has a fine-structure, and in living cells we shall meet with a fine-structure which may even be independent of matter.

When we determine motions, not by the use of measuring rods but by optical instruments, the following elements enter into our description. There is a moving body, there is an optical instrument—which in special cases may be the unaided eye, there is a space between the observer and the observed object and between several observed objects, there is a clock, and there is a light beam, or its equivalent, a stream of moving photons.

REFERENCE FRAMES

In studying the motions of particles, ordinary bodies, the planets in the solar system, the sun and the stars in the galactic system, and of extra-galactic systems we can always describe the motions in different ways depending upon the nature of the reference frames we use. Since we use the incoming light beams in our measurements, the thing we study must obviously be connected with the laws of propagation and the nature of light. In the following I shall first try to show that there are two reference frames which are peculiarly adapted for our study. In the first, the observer is statistically at rest relative to the observable universe or has a uniform motion relative to it; in the second, the observer follows any one particular body freely moving in space. The first observer describes motions in terms of space and time intervals, the other in space-time intervals. The first description, which we will call the "kinematic," has the simplest geometry and gives information about space. The second, which we will call the "dynamic," has the simplest conception of force and gives information about the laws of motion.

Let us first see how we arrive at a kinematic description of motion. We attach a telescope to the earth and study the stars. All celestial bodies seem to turn around a point in the sky called the pole, which itself moves slowly among the stars. The planets move in rather complicated orbits relative to the stars. The near-by stars describe very small parallax ellipses in a period of a year, and all the stars move slowly relative to one another. The last two motions become vanishingly small for very distant objects. All the stars describe aberration ellipses with a semi-major axis of 20″ in a period of a year. The stars have also motions in the line of sight. Finally, the whole system of galaxies expands. The last two types of motions are determined by measuring the shifts of spectral lines, all the others by measuring angular displacements during definite time intervals.

INERTIAL FRAMES

To simplify the description we introduce what has been called an inertial reference frame. Such a frame is defined as non-rotating and non-accelerated. Since all definitions must be made in terms of observations, we must first describe the observational criteria, which determine whether a reference system is an inertial system or not.

Historically, an inertial system was defined as a coordinate system in which a body would move in a straight line with uniform velocity, when no gravitational forces were acting, or when they were compensated by appropriate bombardments by molecules in a direction perpendicular to the force (motion in a horizontal plane). Straight lines were defined by the direction of light beams in media of constant index of refraction or *in vacuo*.

Inertial frames can be determined by reference to the so-called "invariable plane" of the solar system and to the positions of planetary perihelia corrected for mutual attractions between the planets. The accuracy thus obtained is, however, not quite sufficient for precisional astronomy, in particular since we never know if the *empirical* gravitational laws used are exactly correct, or if small attractions from the outside are completely negligible. Instead of the inertial frame defined by moving bodies we now introduce an optical frame defined by moving photons (light beams). The deflections due to gravitational attractions are now very small and only noticeable when the light passes close by another star and proper *empirical* corrections can be applied. With this precaution we can use the optical frame as if it were a rigid frame.

ROTATIONS

The rotation of the earth relative to the inertial frame can be determined without seeing any stars by observation of Foucault's pendulum. The earth's rotation relative to the optical frame can similarly be determined by the use of the interference method of Michelson.[1] In both cases the determinations are of insufficient accuracy.

We have also noticed that the stellar frame moves around the earth with the same angular speed (within the errors of observation) as the earth rotates relative to the inertial and optical frames. We then think of our optical frame as due to a *uniform* structure in space in which light is propagated with a constant, finite velocity in accordance with Euclidean geometry. The stars have small angular transverse motions relative to the same structure, but, by using distant galaxies instead of stars, we can reduce these motions to magnitudes below our observational errors—after corrections have been applied for the effects of yearly aberration—and our stellar frame becomes a rigid structure. We then make the assumption of exact coincidence between the rigid stellar frame, the optical frame and the inertial frame, and we can determine an exact value for the rotational velocity of the earth. The reference to the stars was, if our assumption was correct, for practical and not for principial reasons.

ACCELERATIONS

We shall now see how we can best determine if a reference frame is non-accelerated. The best way of determining small accelerations is by measuring effects of aberration. We then do not have to assume anything as to whether the motions of the observed stars are uniform or not.

Whereas the yearly and secular parallactic dis-

[1] *Astrophysical Journal*, 61: 137, 1925.

placements of the stars are simply explained as effects due to transverse motions of the stars relative to a frame whose origin is fixed in the earth and defined in direction by a few very distant objects, the large yearly swing of the light beams common to all stars in the same region of the sky and called aberration is more fundamental. The simplest and most obvious way of explaining it is by assuming the earth to have a non-uniform motion relative to an inertial frame in which light is propagated, or in which photons move, according to simple rules. For this reason, the observed object must not be too close, since in this case the motion of the observer is sensibly uniform during the time it takes light to travel from the source to the observer. The periodic aberration changes give a measure of the *observer's* acceleration, and the reference frame is the space structure characteristic for an inertial frame. If we used a reference frame fixed to the earth and if we used Euclidean geometry—as we have the right to do since the bending of the light beams due to the stars' attraction is entirely negligible, we must conclude that all the stars moved in ellipses whose linear size *increased* with increasing distance. Since we do not observe any masses, which we should expect to be associated with the tremendous accelerations of distant objects, we conclude that the acceleration so determined is a relation between the observer and the space around him and has nothing to do with the observed objects, except possibly in a statistical sense, which will be explained later.

A reference system fixed in the center of mass of the solar system can not have any large periodic accelerations without producing corresponding periodic aberration effects. Can we tell if it has an acceleration constant during a long time interval? The aberration measures the velocity of the observer relative to another inertial frame than the one in which he is at rest. If this velocity is constant no observable change is produced. If the aberration is different at two epochs, we can conclude that the motion of the observer is accelerated. It can easily be shown that the mean acceleration perpendicular to the line of sight is equal to the mean time-rate of change of aberration multiplied by the velocity of light. It seems now as if it should be easy to determine the constant acceleration of the sun simply by measuring the systematic proper motions of the stars, the aberration effects being separated from the parallactic displacements by making use of the fact that the latter decrease with increasing distance, whereas the former are independent of distance. It is not so simple, however. If the whole galaxy should have a uniform acceleration, the corresponding field of force would, according to the postulate of the general theory of relativity, bend the light beams just enough to exactly compensate for the aberration. We have then to use extra-galactic objects for our determination. We have reason to believe that the systematic proper motions of these objects do not exceed 0.″01 per year, after corrections for yearly aberration have been applied. Hence we conclude that the acceleration of the sun and the galaxy as a whole can not exceed 0.00005 cm/sec^2. Relative to what is this acceleration measured? It certainly is not relative to the particular objects observed, since we know from observations of double stars that the accelerations of the individual stars have no effect on the aberration. If we used the same reasoning as we did for the earth's motion around the sun we would conclude that it was relative to the space structure characteristic for an inertial frame, and the acceleration could in this sense be termed "absolute." On the other hand, we must admit that we had to use external objects for its determination and, although the acceleration is not relative to the group of objects observed, it may still have some connection with the whole system of observed and unobserved cosmical objects.

The phenomenon seems to be very much the same as in the case of the "absolute" rotation of the earth. We can not measure the latter by observation of aberration effects on terrestrial light sources. In the first place, the effects would be inconceivably small, due to the fact that the velocity of the observer does not change appreciably during the short time it takes light to travel from a terrestrial object to an observer. In the second place, the relativity theory postulates that there would be strains in the earth and bending of light in the vertical plane, in which the measures have to be performed, which together would just compensate for the expected effects. One reason we still may think that the rotation of the earth is absolute is that it can be determined by measuring space derivatives instead of time derivatives, as Michelson has done.

We have now given the observational criteria needed for determining whether a reference frame is an inertial frame or not. The result is that a reference frame fixed to the center of mass of the solar system, rotating with the same speed as the system of extra-galactic objects, fulfills our requirements with a very high degree of precision. We must not forget, however, that an exact coincidence between the stellar frame and the inertial frame, so far as rotation was concerned, was assumed without proof.

The expansion of the system of galaxies does not produce any change in the angular separation of the galaxies, when measured from any one of them, since it is only a progressive change in scale.

The views expressed here about the nature of rotations and accelerations are not generally accepted, but they are, I think, in harmony with those of Einstein. I quote from his Leyden lecture[2] of 1920: *"Newton might no less well have called his absolute space 'Ether'; what is essential is merely that besides observable objects, another thing, which is not perceptible, must be looked upon as real, to enable accelerations or rotations to be looked upon as something real."* The "other thing" (Kant's "Unding") has here been called "space structure."

The special theory of relativity postulates that all inertial systems are equivalent for the description of motion and of electromagnetic phenomena. By no means can we single out any unique inertial system which has other properties than all other inertial systems. This may well be true.

Uniform Motions

A few words may be added, however, about the effects of uniform motion relative to an inertial frame. If a body is moving relative to an observer it is contracted in conformity with Lorentz' expression. A moving clock goes slower than a similar stationary clock.[3] These are observable effects, dependent upon motion relative to an actual observer and can be regarded as due to the geometry of light propagation and the finite velocity of light equally well as to a property of space.

When light is traveling inside a moving transparent body the space structure is carried along with the material structure with a certain fraction of its velocity in conformity with Fizeau's formula. This is also an observable effect verified by interference experiments. We can then explain why the aberration is the same for a telescope filled with water and for one filled with air (Airy's experiment). From these considerations follows the addition law of velocities in the special theory of relativity, and an upper limit can be deduced for the *observed* velocity of a body relative to an observer.

Relativity Effects in Kinematic Terms

We can go a few steps further in our kinematic description. By a slight modification of our law of gravitation and by giving mass to a photon we can "explain" the motion of the perihelion of Mercury and the deflection of a beam of light near the sun's limb, provided we determine these effects *empirically*. There still remains the red-shift of the general relativity theory. We have *empirical* reasons to believe that a photon has a mass and carries momentum and energy. The sun's gravitational field holds back the photon and it loses momentum and energy. Since it can not change its velocity, the loss of "kinetic" energy must correspond to a reduction of the frequency, and we arrive at the same formula as that given in the general theory of relativity, seemingly verified by observations. We conclude that the original frequency of the light emitted by a certain transition in an atom was originally the same as for a similar atom on the earth.

To summarize the kinematic description, we can make the following statements. Rotations and accelerations are not determined relative to any observable bodies, but can be regarded as referred to the uniform space structure of an inertial frame, and are in this sense absolute. Euclidean geometry can be used for light beams if we apply the proper corrections due to gravitational forces and to the finite velocity of light. All inertial systems are equivalent for the kinematic description of motion; in particular is the *measured* velocity of light the same in all of them. There may exist a unique inertial frame in which light travels with a unique velocity, but since we can not observationally discriminate between such a frame and other inertial frames, this conception may be an illusion. These statements do not lead to any discrepancy with observations hitherto made.

Dynamic Description

The kinematic description of motion has in its favor the simplest possible geometry, but it leaves the forces out as something extraneous and disturbing, not explicable in quite the same language as inertial motion. Einstein's general theory of relativity has made it possible to express inertial and non-uniform motion as being both properties of a non-uniform space-time structure. The motion is now always uniform or zero, but our new reference frame in space and time is different here and there, now and then. In other words, it is distorted, particularly so in the neighborhood of what we call matter. Particles, photons and stars follow "world-lines" in space and time. The world-lines are dependent upon gravitational potentials, and when two world-lines meet we have an *"event"* observable in space and time. The potentials determine the space-time geometry, which is now empirical, to be determined by measurements in space and time.

This is not the place to go into any details of the general theory of relativity. For our purpose it is sufficient to say that a modification of Newton's law of gravitation can be derived from the assumption of equality of all reference frames of the same "kind."

[2] "Ether and Relativity," *Sidelights on Relativity*, Methuen, 1922.

[3] There is also an effect of the first order in v/c (Doppler effect), which may make the clock appear to go faster or slower, according as it approaches or recedes from the observer. After this has been allowed for, there remains a second order effect here referred to.

Several of the relations mentioned in the kinematic description can be derived without introduction of new empirical constants, which relations have been verified by observations. An important consequence is that of the equivalence between mass (matter) and energy. Since motion is dependent upon space-time structure, which in its turn is dependent on matter, it must of necessity be relative to matter or rather to the metrical field associated with matter. By arbitrary transformations of coordinates we can introduce new acceleration fields, which are identical with gravitation fields, except that they are not associated with matter. For an *actual* freely moving observer the actual field equations must be used, and we then always find matter associated with the acceleration fields.

(*To be concluded*)

OBITUARY

WILLIAM PATTEN

STILL vigorous and actively engaged in scientific research at the age of 71, Dr. William Patten suddenly and peacefully passed away at Hanover, New Hampshire, on October 27, 1932. He had just returned from an expedition to the Baltic Island of Oesel, Esthonia, where during the summer with a large corps of workmen he had exhumed and shipped to Dartmouth College a large collection of primitive fossil fishes, chiefly small, delicate Ostracoderms. It had been a successful expedition, and he felt that, after three seasons of intensive work, the region visited had been thoroughly explored.

His enthusiastic, day-and-night application to the preliminary survey of his fossils was too strenuous. Six days before his death a painful heart attack struck him down. He rallied and hoped soon to return to his work, when suddenly, by coronary thrombosis, the end came.

Born at Watertown, Massachusetts on March 15, 1861, the youngest son and next to the youngest child in a family of 14 children, his bent toward zoology was shown, even before he entered the Lawrence Scientific School of Harvard University, by his interest in ornithology and anatomy. While in college he paid his expenses in part by work at taxidermy and the illustration of scientific books. As a freshman he won the Walker Prize of the Boston Society of Natural History by a paper on the "Myology and Osteology of the Cat," work which had been done mostly before entering college.

Professor E. L. Mark, under whom he studied zoology at Harvard, found him a brilliant student, independent and energetic. He was also under Professor Shaler's stimulating influence. His perennial interest and skill in athletics was shown by his position as catcher on the Watertown baseball team; his love of music by his membership as a tenor in the Harvard College choir and glee club.

He received the B.S. degree in 1883, was awarded a Parker traveling fellowship and married Mary Elizabeth Merrill, of Bradford, Massachusetts, who became his lifelong companion.

Studying at the University of Leipzig under the distinguished zoologist, Leuckart, he received the degree Ph.D. at the end of the first year (1884). Two years of research followed, first at the Zoological Station at Trieste, then at Naples. Returning to America in 1886, he was for three years assistant to Dr. C. O. Whitman at the Allis Lake Laboratory at Milwaukee. His son, Dr. Bradley Merrill Patten, associate professor of histology and embryology at the Western Reserve University School of Medicine, was born at Milwaukee in 1889. From 1889 to 1893 William Patten was professor of biology at the University of North Dakota.

Coming to Dartmouth College as professor of biology in 1893, he brought with him a strong urge toward research. Soon there were graduate students working under his instruction on *Limulus* and arachnid embryology. While teaching comparative anatomy of vertebrates and embryology, which he did for 25 years, he organized a course centered about organic evolution.

Desirous of contacts with younger students, he undertook in 1920–21 the organization and became the director of the freshman course in evolution, which he conducted with the cooperation of several associates until his retirement from teaching in June, 1931, at the age of 70, at which time he received from Dartmouth the honorary degree of Sc.D.

His scientific publications between 1884 and 1889 were upon the embryology of insects (Phryganids) and mollusca (*Patella*) and upon the eyes of mollusks and arthropods, described in extensive papers with clear and beautiful illustrations. From 1889 to 1900 his work centered about the king crab, *Limulus,* especially its nervous system and embryology. The first statement of the theory which dominated his later research, "On the Origin of the Vertebrates from Arachnids," appeared in the *Quarterly Journal of Microscopical Science* in 1889. This hypothesis was also elaborately developed and illustrated with a wealth of new observations in his book, "The Evolution of the Vertebrates and Their Kin," published in 1912.

Since 1900 his numerous papers have followed two quite different lines, paleontology of primitive fishes,