FROM
COPERNICUS
TO
EINSTEIN

HANS
REICHENBACH

Translated by
RALPH B. WINN

Dover Publications, Inc.
New York

Published in Canada by General Publishing Company, Ltd., 30 Lesmill Road, Don Mills, Toronto, Ontario.
Published in the United Kingdom by Constable and Company, Ltd., 10 Orange Street, London WC2H 7EG.

This Dover edition, first published in 1980, is an unabridged and corrected republication of the English translation first published in 1942 by Philosophical Library, Inc.
The work was originally published in 1927 by Ullstein, Berlin, under the title *Von Kopernikus bis Einstein.*

International Standard Book Number: 0-486-23940-3
Library of Congress Catalog Card Number: 79-055911

Manufactured in the United States of America
Dover Publications, Inc.
180 Varick Street
New York, N.Y. 10014

CONTENTS

CHAPTER

ILLUSTRATIONS

Chapter 1 : THE COPERNICAN VIEW OF THE WORLD

THIS little book purports to serve as an introduction to the great problems of space, time and motion. The inquiries it is concerned with are very old. Men have been forming ideas concerning space and time since times immemorial, and curiously enough, have been writing and fighting about these things with the greatest interest, even fanaticism. This has been a strange strife, indeed, having little to do with economic necessities; it has always dealt with abstract things, far removed from our daily life and with no direct influence upon our daily activities. Why do we need to know whether the sun revolves around the earth or vice versa? What business of ours is it, anyway? Can this knowledge be of any use to us?

No sooner have we uttered these questions than we become aware of their foolishness. It may not be of any use to us, but we want to know something about these problems. We do not want to go blindly through the world. We desire more than a mere existence. We need these cosmic perspectives in order to be able to experience a feeling for our place in the world. The ultimate questions as to the meaning of our actions and as to the meaning of life in general always tend to involve astronomical problems. Here lies the mystery surrounding astronomy, here lies the wonder we experience at the sight of the starry sky, the wonder growing in proportion to our understanding of immense distances of space and of the stars' inner nature. Here is the source of scientific as well as popular astronomy.

These two branches have diverged in the course of their development. Astronomy, as a science, has come to forget its primitive wonder: instead, it approaches the realm of stars with sober research and calculation. This disenchantment with its subject-matter, which scientific study invariably entails, has permeated astronomy to a greater degree than the layman realizes. In observing the astronomers of today, how they measure, take notes, calculate, how little attention they pay to mysterious speculations, one may be surprised to find the wonderful structure of learning so cut and dry at a close range. Yet nothing is more wrong and more objectionable than the feeling of a heartbreaking loss, with which some people regard the vanishing mysticism of the skies. Although science may have destroyed a few naive fantasies, what she has put in their place is so immensely greater that we can well bear the loss.

It takes perseverance and energy, of course, to comprehend the discoveries of science; but whoever undertakes the study is bound to learn many more surprising things from it than a naive study of nature can disclose. Scientific astronomy has always exercised, in fact, a great influence upon everyday thinking and upon the popular conception of the universe. If it is difficult today to pronounce the name of Copernicus without thinking of a turning point of history, it is not only because the name is connected with a profound transformation in the science, but also because all our knowledge and thinking have been deeply affected by his discovery. The statement that the earth does not occupy the center of the world means more than an astronomical fact; we interpret it as asserting that man is not the center of the world, that everything which appears large and mighty to us is in reality of the smallest significance, when measured by cosmic standards. The statement has been made possible as a result of scientific development in the course of thousands of years, yet it definitely contradicts our immediate experience. It takes a great deal of training in thinking to believe in it at all. Nowadays we are no longer conscious of these things, because we have been brought up since childhood in the Copernican view of the world. However, it cannot be denied that the view belies the testimony of our senses, that every immediate evidence shows the earth as standing still while the heavens are moving. And who among us can declare in all seriousness that he is able to imagine the tremendous size of the sun or to comprehend the cosmic distances defying all earthly ways of measurement? The significance of Copernicus lies precisely in the fact that he broke with an old belief apparently supported by all immediate sensory experiences. He could do it only because he had at his disposal a considerable amount of accumulated scientific thought and scientific data, only because he himself had followed the road of disillusionment in knowledge before he glimpsed new and broader perspectives.

If we endeavor to trace, in the following pages, the development of the problems of space and time, beginning with the discovery of Copernicus and closing with the still less accessible theory of the Copernicus of our day, we have no other alternative than to apply hard scientific thought to every step of the way. We must add that the discoveries of modern science have been made possible only by the abundance of new scientific materials. Einstein's doctrines are by no means an outgrowth of astronomical reflections alone; they are grounded in the facts of the theory of electricity and light as well. We are able to comprehend them only insofar as we get acquainted with all of their sources. This derivation from several sources is characteristic of the theory of relativity. While the modern source gave rise to the special theory of relativity, the older sources provided the material for the construction of the general theory of relativity, in which the old and new knowledge became blended in a magnificent unity.

In this chapter we shall deal with old material; in the next two chapters we shall present the special theory of relativity and its origin; and the last three chapters will be devoted to the blending of the material and, therefore, to the general theory of relativity.

The world-picture found by Copernicus goes back to the ancient Greeks. It was systematized about 140 A.D.

by Ptolemy Claudius of Alexandria and outlined in his famous work *Almagest.* The most important feature of the Ptolemaic scheme of the universe is the principle that the earth is the center of the world. The heavenly globe revolves around it; and Ptolemy knew full well that it has the same spherical shape below the horizon, which it assumes above the horizon. In fact, Ptolemy knew even that the earth is a sphere. His proofs to this effect reveal a great knowledge of astronomy. He shows, first of all, the existence of curvature from north to south. As the Polar Star stands higher in the north and lower in the south, the surface of the earth must be correspondingly curved. The proof of the existence of curvature from west to east reveals even better observation. When the clocks are set by the sun in two places located west and east, and when an eclipse of the moon is thus observed, it will be seen at different times. However, the eclipse is a single objective event and should be seen everywhere at the same time. Hence we conclude that the clocks at the two places are not in accord. This can be accounted for by the curvature of the earth in the west-east direction: the sun passes the line of the meridian at different moments in different places.

In spite of the recognition of the spherical shape of the earth, Ptolemy was far from admitting its movement. He contended, on the contrary, that it was impossible for the earth to be moving at all, either in a rotating or in a progressive manner. As far as the former is concerned, he admitted the possibility of such an opinion, as long as the movement of the stars was considered. However, when we take into consideration everything that happens around us and in the air, this view—so he argues—becomes obviously absurd. For the earth, during its rotation, would have to leave the air behind. Objects in the atmosphere, such as flying birds, not being able to follow the rotation, would have to be also left behind. A progressive motion of the earth is equally impossible for, in that case, the earth would leave the center of the heavenly sphere, and we would see by night a smaller part of the sphere and by day a larger one.

One can see from these arguments that the great astronomer has devoted much serious thought to the problem. In the light of his rather limited knowledge of mechanics and of the heavenly spaces, his reasoning must have seemed quite conclusive. As far as his last objection was concerned, he could not have suspected that the interstellar distances were so great as to make the lateral shift of the earth completely unnoticeable.

The planets are characterized, according to Ptolemy, by common movements. Their path, as observed in the sky, is determined by superimposed circular orbits. As a result, there arise the so-called "epicycles." One must admit that Ptolemy has deeply understood the nature of planetary movements. When one gets acquainted with the Copernican conception, one discovers the facts revealed behind Ptolemy's epicycles: the loop of the planets' course mirrors their double motion as regards the earth. In the first place, they move in a circle around the sun, and in the second place, this movement is observed from the earth which, in its turn, revolves around the sun.

The Ptolemaic conception of the universe dominated the learned people's minds for more than one thousand years. The man who undermined this firm tradition—Nicholas Copernicus—required great independence of thought as well as great scientific knowledge, for only an insight into the ultimate relations of nature could give him the ability to discern new approaches to truth.

The canon of Frauenburg was long known as a learned astronomer before his new ideas were presented; he had studied in Italy all branches of science, he had acted as doctor and church administrator in his home town, and his astronomic knowledge was so well recognized that in 1514 he was asked by the Lateran Council for his opinion on questions of calendar reform. His new ideas concerning the system of the universe were formed, in their essence, at the age of 33. However, he did not promulgate them at that time, but devoted the following years to a thorough elaboration and demonstration of his theories. Only excerpts of his doctrine were published during his lifetime. His main work entitled "Of the Rotation of Celestial Bodies" appeared only after his death in 1546. He read the proofs only on his death-bed and thus failed to notice that his friend Osiander supplied the work with a foreword which contained a cautious compromise with the opinions of the Church.

If we examine the proofs given by Copernicus of his new theory, we find them quite insufficient from the point of view of present-day knowledge. He was able, in fact, to cite as a distinct advantage only the greater simplicity of his system. He regards it as improbable that the stars move with great speed in their large orbits and finds it more likely that the earth rotates on its axis, so that the speed of motion in each particular point is considerably smaller. Against Ptolemy's objection to this he urges that Ptolemy considered the rotating movement of the earth as implying force, whereas it is simply natural; its laws differ completely from those of a sudden jerky movement. All of this is certainly inconclusive. We know today that Newton's theory contains the first real proof of the Copernican conception of the universe. But it seems that new ideas are able to gain foothold by the sheer power of their inherent truth long before their objective verification has been obtained.

On the other hand, it is very important to acknowledge that the Copernican theory offers a very exact calculation of the apparent movements of the planets and that the tabulations (the so-called "Ephemerides") accompanying it are far superior to the older ones. Here lies one of the reasons which led the scientists to accept the Copernican system, even though it must be conceded that, from the modern standpoint, practically identical results could be obtained by means of a somewhat revised Ptolemaic system. Furthermore, Copernicus calculated quite accurately the radii of the planetary orbits (within less than 1%). In fact, he knew already that the sun must be

slightly off the center of the solar system, for an assumption to the contrary led to estimable discrepancies.

Yet there was still a long way from this discovery to the recognition of the elliptic shape of the orbits; any conclusive evidence to this effect required above all better astronomic instruments. In this important connection, we must consider Tycho Brahe who is less prominent as a theoretician than as a builder of outstanding instruments. Brahe was able to work for many decades under the protection of the Danish king. He built the castle Uranienburg on an island, to which was attached a large settlement where precise instruments were prepared for him in special plants. It is amazing how the precision of instruments was increased in this manner. For instance, Copernicus had to be satisfied with measurements within 10' of the arc. This corresponds approximately to an angle covered by a five-pence piece at a distance of six meters. Tycho increased the precision to within half a minute of the arc. This angle would be enclosed by the same coin at a distance of 120 meters. With the instruments of today, of course, angles can be measured within one hundredth of a second of the arc. The coin would have to be placed at a distance of 360 kilometers to enclose such a small angle.

This precision we owe mainly to the use of the telescope. Tycho had to work without a telescope. One of his sextants with which he conducted his observations of Mars still stands in the Prague observatory, where Tycho, exiled from Denmark, spent the last years of his life (c. 1600).

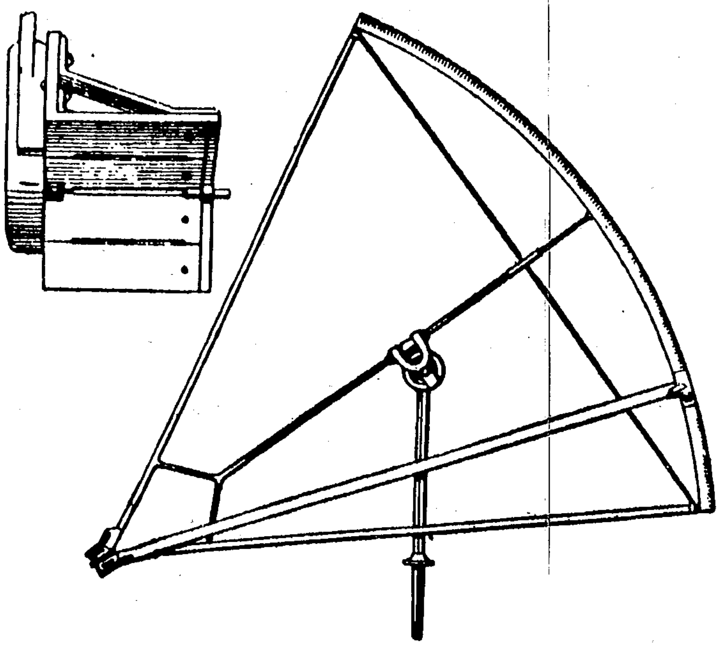

Figure 1. A Tycho Brahe's Sextant

Figure 1 shows the picture of this historic instrument. The pointed leg is set in a stand. The whole instrument is movable at the hinge in the upper end of the leg. It measures 1½ meter at the shank. The shank may be turned and has a sight-hole at the bottom to the left, an ironplate with a slit, through which a sharp edge on the upper end of the shank (to the right) is adjusted. This endpiece slides along an angle-scale. The sight-plate itself measuring several centimeters is reproduced in an enlarged form at the upper left corner. By means of such a crude-looking apparatus, Tycho found the data on which modern astronomy is historically resting.

The man who continued Tycho Brahe's work was his assistant Johann Kepler whose name surpasses by far that of his master. Kepler carried on his observations with the sextants of Tycho. He determined the course of the motion of Mars by means of so many individual observations that he was able to pronounce it with certainty as elliptical in shape. He discovered through mere measurement also other laws of planetary motion, called after him "the Kepler's laws." One must admire the strength of character of this man, which manifests itself in his zeal for factual accuracy. Kepler was at first a mystic and speculative dreamer, disinclined to sober observations. He concentrated in his early works on searching for strange mathematical 'harmonies' of nature, and such a goal inclines one to distort facts rather than to establish them. It remains true, however, that Kepler has accomplished much more for his own aim by his zeal for factual accuracy than by his speculations. He himself expresses this thought. In his work entitled "Harmony of the World," which appeared in 1619, he writes concerning the discovery of his laws: "At last I have found it, and my hopes and expectations are proven to be true that natural harmonies are present in the heavenly movements, both in their totality and in detail—though not in a manner which I previously imagined, but in another, more perfect, manner. . . If you forgive me, I shall be glad; if you are angry, I shall endure it. Here I cast my dice and write a book to be read by my contemporaries or by the future generations. It may wait long centuries for its reader. But even God himself had to wait for six thousand years for those who contemplate his work."

We must not forget, however, that, though the astronomic picture of the universe was considerably advanced, in regard to precision, by Kepler's discoveries, nevertheless, that world-view, though basically Copernican, differed very considerably from our Copernican idea of the world. Copernicus as well as Kepler was of the opinion that the solar system virtually exhausted the space of the universe. The stars, according to them, were tiny dots in the sphere of heavenly matter, which circumscribed the whole of space. When Giordano Bruno expressed his thoughts on the infinity of the firmament and maintained that fixed stars were independent solar systems, Kepler proceeded immediately to combat the idea. How difficult it must have been to climb the stairs leading to our present-day knowledge!

Astronomy made its decisive advance over Kepler's knowledge again through an improvement in the means of observation — through the invention of the telescope. The great merit of having made the first serviceable telescope and of having used it for the observation of the sky belongs to Galileo; though not the original inventor of the telescope, he constructed it after hearing of such instruments. He directed his telescope toward the moon and recognized the spots on the moon, on account of their

jagged outline and shifting illumination, as tremendous mountains (1610). He pointed it towards Venus and saw its sickle-like shape, similar to that of the moon, which it periodically assumes as a result of receiving light from the sun. He directed the telescope towards Saturn and saw its 'triple' figure the details of which he could not yet discern. He directed it towards Jupiter and saw its satellites (the four brighter ones) designated by him as "medizeic planets."

All these facts, with their enlargement and enrichment of the Copernican world, must have greatly astonished his contemporaries. It also provoked, to be sure, the opposition of the old school of scientists who saw their tenets grounded in Aristotle seriously endangered. Galileo's most precarious position can be best envisaged from a letter written by him to Kepler: "I am very grateful that you have taken interest in my investigations from the very first glance at them and thus have become the first and almost the only person who gives full credence to my contentions; nothing else could be really expected from a man with your keenness and frankness. But what will you say to the noted philosophers of our University who, despite repeated invitations, still refuse to take a look either at the moon or the telescope and so close their eyes to the light of truth? This type of people regard philosophy as a book like Aeneid or Odyssey and believe that truth will be discovered, as they themselves assert, through the comparison of texts rather than through the study of the world or nature. You would laugh if you could hear some of our most respectable university philosophers trying to argue the new planets out of existence by mere logical arguments as if these were magical charms." Galileo relates how another scientist refused to take a look through the telescope "because it would only confuse him." The tragic fate of Galileo, caused by such antagonism, is well known. He had to pay with many years of incarceration and imprisonment for his sponsorship of the Copernican theory.

Another achievement of Galileo had apparently no direct connection with astronomy; but this connection was discerned soon enough. Galileo was the first man to investigate the laws of falling bodies. He has thereby established the basic laws on which the science of mechanics was destined to grow. The apparatus he built was quite primitive. For instance, he had no watch in the modern sense of the word, but had to measure time by means of water running out of a vessel. In spite of everything, he was able to determine the relationship between the distance and the time of the fall, and also the law of acceleration. He also discovered the fact — a most surprising fact for his day — that all bodies fall equally fast. Finally, he formulated the basic law of motion, named after him: that every body unaffected by external forces moves in a straight line at a uniform speed, and that this motion can never stop by itself.

Although these laws seem to be merely bits of factual information, nevertheless they signify an extraordinary progress as compared to the preceding era. There was no inclination at that time to collect data. It was believed that all one wanted to learn could be disclosed by speculative thinking. Galileo's great achievement was that he resorted to direct investigation of nature. Moreover, the facts he discovered were destined to attain a significance far beyond their own realm, namely, when Newton constructed the mechanics of heavens on them.

Fate allotted to the English physicist Isaac Newton (1643-1727) an outstanding role in the history of the natural sciences of the described period. He was the great unifier who combined the individual discoveries of Copernicus, Kepler and Galileo into one magnificent system. His intellectual achievement cannot be estimated too highly. With the vision of a genius he realized that the power of gravitation perceived by Galileo in his doctrines concerning falling bodies had a significance far transcending the region of the earth, that this power of attraction constituted a property of all mass, and that it determined the planets' behavior across cosmic distances. This far-reaching insight into the nature of things was accompanied by Newton's great caution in scientific investigation. He started with the correct premise that the power of attraction must diminish with distance. He then calculated what the magnitude of this power, already estimated by Galileo on the surface of the earth, could be at the distance of the moon. Next he computed the length of time required for the revolution of the moon around the earth, if this gravitational power was indeed responsible for the motion of the moon. All this was a magnificent elaboration of the original idea. Unfortunately, luck was against Newton, and his investigations resulted in anything but agreement with facts. Yet nothing shows better the greatness of the scholar's character than his conduct in the face of failure: he put his calculations away in a closet without publishing a single word concerning his profound meditations (1666). Only twenty years later could the mistake be explained. The length of the earth's radius, taken by Newton as the basis of his calculations, had been inexact; new estimates on the astronomers' part gave a new measurement with which Newton's reflections about the moon proved to be in full accord.

The mechanics of Newton has thus received confirmation, and it must have seemed like a magic key to his contemporaries. His theory transformed the fundamental facts of the preceding centuries into a uniform system, including the Copernican theory of the heliocentric motion of the planets, Kepler's laws concerning their orbits, and Galileo's laws of falling bodies in a gravitational field. Kepler did not live to greet this triumph of thought; no doubt, he would have rejoiced over this proof of the harmony of cosmic motions.

The Copernican conception of the universe was at last scientifically established, insofar as the laws underlying it stood revealed. Up to that time the Copernican conception of the universe, as compared to the Ptolemaic conception, could justify itself only by its claim of representing the world-picture in simpler terms. But now,

with the addition of Newtonian mechanics, it became the only acceptable one. Its real merit was made explicit: the Copernican conception of the world provided an explanation of natural phenomena, a cosmic order governed by laws. It was the destiny of the Western mind to absorb this worldview which so much corresponded to its innate tendencies of thought.

Thus ends the first period of new physics; and with it has come a new method of inquiry to dominate the natural sciences ever since. The collection of facts is the starting point of investigation; but it does not mark its end. Only when an explanation comes like a bolt of lightning and melts separate ideas together in the fire of thoughtful synthesis, is that stage reached which we call understanding and which satisfies the seeking spirit.

The following chapters will show how widely and how consciously new physics has carried through this method of inquiry.

Chapter 2 : ETHER

WE HAVE already pointed out, in connection with the Copernican picture of the world, that the astronomic problems of motion and gravitation represent one of the sources from which the theory of relativity has sprung. Its other source lies in the theory of electricity and in that of light. We shall now concern ourselves with its development from this latter source; and in so doing, we shall follow the trend of development characterizing the modern conception of the physical universe. The truth is that the science of physics was forced to go beyond the views of Copernicus, Galileo and Newton by questions arising in connection with electricity and optical phenomena. These men, considered as innovators at their time, experienced all the inimical resistance of an outworn age still fighting for its existence, as we can judge from Galileo's tragic words quoted above. For the succeeding period the same men represent the classics, the great authorities who have dominated the thoughts of a whole era and whose work was carried on by generations of scholars; and the younger generation has to fight against them a battle similar to that which made those men famous.

It seems that progress in the knowledge of nature can be made only through conflict between two successive generations. What is considered at one time as a revolution of all thinking, a tempest in the brain, is for the next age a matter of fact, a school knowledge acquired under the influence of one's environment and believed and proclaimed with the certainty of everyday experience. Thus, possible criticism to which even the greatest discoveries should be continuously submitted, is forgotten; thus we lose sight of the limitations holding for the deepest insights; and thus man forgets in his absorbing concern with the particulars to re-examine the foundations of the whole structure of knowledge. We shall always have to depend on men like Copernicus who question obvious matters and whose critical judgment penetrates deep into the foundations of truth.

The history of the study of light illustrates this process. For it represented a definite attempt to comprehend the phenomena of light on the basis of ideas aroused by new astronomy and mechanics; it was an attempt to make mechanics the last court of appeal, the ultimate foundation of all knowledge. But this attempt failed. It turned out that the problem of light, too, can be solved only in a Copernican fashion, insofar as mechanics was unable to explain electrical and optical phenomena, but, on the contrary, had to be explained by them. This was a tortuous road marked by continual frustrations. Whenever new theories have been constructed, there appeared also new experiences accentuating the inadequacy of the solution that had been achieved.

The first and most important step toward the understanding of light was taken already at Newton's time by the Danish astronomer Olaf Roemer. It was a discovery of profound significance; in the year 1676 this astronomer determined the velocity of light and thus discovered, not only a new numerical result, but also a new physical concept. Up to that time the idea that light required time to propagate did not occur at all to anybody. Among the scholars only a few outstanding minds had foreseen the possibility of such a fact. Nowadays, when the younger generation acquires this information on the school-bench, it is taken as a matter of fact; but one should understand to what extent it contradicts immediate experience. It seems natural to us to think that light fills the room the moment we switch on an electric lamp; actually this is not at all the case, for light spreads gradually from the electric bulb and its environment to the rest of the room. The word 'gradually' is here used, of course, in a figurative sense: the process of the propagation of light takes in this case less than one-millionth of a second. This immense velocity of light was the main reason why the character of light as a spreading process could be recognized only at a late period. Only exceedingly exact measurements could determine the minute periods required for the propagation of beams of light.

This discovery remained therefore reserved for astronomy, a science combining precision of measurement with the observation of tremendous distances; it offered suitable conditions for the determination of the velocity of light. Olaf Roemer investigated the eclipses of Jupiter's satellites; he watched the disappearance and re-appearance of these moons when, in their orbital motion, they passed the cone-shaped shadow of the planet. As a result, he found that the durations of such darkenings of the moon were not always precisely the same but varied by seconds, according to the time of the year. Such little deviations from exact figures led more than once, in the history of science, to deepest insights into the nature of the world. It is as if nature discloses its fundamental relationships in the minute errors of current theories.

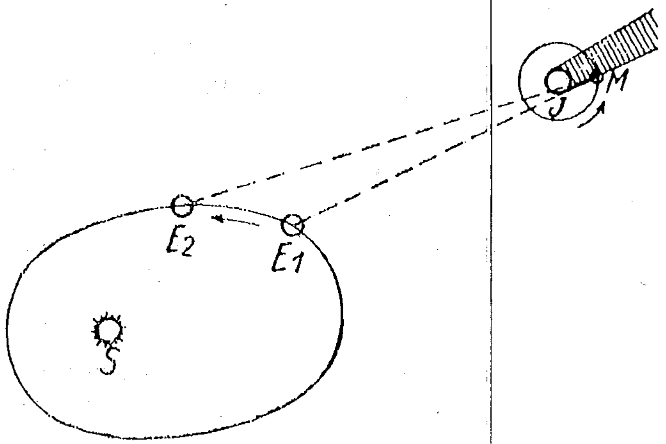

Fig. 2. Roemer's Observation of Jupiter's Moon

In Roemer's case, the existence of a velocity of light was inferred from such deviations in observations, and even the numerical value of this velocity could be calculated rather exactly. The trend of his thought can be understood, when Figure 2 is examined.

The path of the earth is here portrayed as an ellipse with the sun (S) occupying one of its foci. Jupiter (J), with the orbit of one of its moons, is found to the right (It is understood that the limitations of the diagram make it impossible for us to give a true picture of distances and sizes). When the moon enters the conical shadow of Jupiter at point M, it sends the last beam of light, reaching the earth several minutes later at point E^1. After a few days the moon emerges from the conical shadow, turns slowly around Jupiter and reaches once more point M (In reality, this is not the same point M, insofar as Jupiter with its moons will have moved forward; but this movement is very slow and can be disregarded in our explanation). At the moment of this second disappearance, the moon sends again its last beam to the earth. The latter has moved in the meantime to E^2, however, so that the beam has now a longer trip to make. Had the earth remained at E^1, the astronomer would notice the disappearance of the moon at M every time after a definite interval corresponding to the time required by the light to traverse the distance ME^1. On both occasions the delay would be the same, and the duration of a complete orbital course of the moon would be found identically correct. But the earth has not remained standing still but has moved in the meantime to E^2. Light has now a longer route ME^2 to traverse, and the excess of time required for it becomes responsible for a faulty prolongation of the orbital period. As the correct duration of each revolution of the moon is known from other sources (which cannot be here discussed), and as the distances ME^1 and ME^2 can also be estimated, the difference between the two intervals of time required for the propagation of light can be readily calculated. The time required by light to traverse a distinct distance becomes thus known, and the velocity of light can be immediately determined.

Roemer's discovery was known to Newton, whom we meet here in an important role, not only in connection with mechanics but also in that with optics. Newton explained the propagation of light as the emission of tiny particles thrown into space and capable of passing through air and gases by virtue of their smallness. He was able to account for many optical phenomena by means of this *theory of emission* of light. His doctrine dominated the physical interpretation of the world for one century, even though there was formed at that time the wave theory of light, which replaced Newton's conception at a later date.

It was the mathematician Christian Huyghens who recognized, with remarkable keenness, the possibility of explaining all phenomena of light-transmission by means of wave-propagation. His theory found acceptance in the scientific circles with considerable difficulty mainly because he put as it were the cart before the horse. It was eminently suited to explain quite simply the phenomena discerned in difficult optical experiments; but when it came to the most ordinary, easily observable facts of light-propagation, it had only extremely involved explanations to offer. Thus, it made the phenomena of the bending and

interference of light easily understood; but the rectilinear propagation of light, occurring in daily experience as one of its most conspicuous characteristics (e. g. in the formation of shadows), could be conceived only as a very complicated process arising out of a peculiar superposition of light waves coming from various directions. That is why science had to cling to the emission-theory of light as long as there remained hope for Newton's theory to explain the phenomena found in experimentation, no matter in how intricate a manner. When finally, under the pressure of the results of additional experiments of great merit, the wave-theory won, it was shown that the principle, often regarded as self-evident, that 'natural' phenomena are basically 'simple', did not always hold true. Rather, it must be said today that, in general, the simplest relations in nature hardly ever appear "naturally", but must be created in laboratory conditions by means of an artificial control of active factors. The simplicity of natural processes, on the contrary, appears as an illusion due to the confluence of intricate factors. Whoever looks from a high mountain at the smooth surface of the sea, will not be inclined to think that, in reality, it has the character of a wave-like curved surface; rather, he will visualize it on a large scale and consider it as a plane. Similarly, when we face nature in everyday experience, we see it only in a broad outline. It takes the sharp eyes of science to notice behind it the intricate pattern of interconnected factors and to recognize in them the true configurations of natural forces.

The history of scientific optics is a continuous triumph of systematic methods over naive beliefs. It is easy to understand, therefore, that men outside the field of the natural sciences, whose outstanding achievements in other subjects were a result of straight-forward thinking and immediate relationship to nature, attacked again and again scientific optics for being essentially on the wrong path. Such individuals as Goethe and his various adherents failed to see that the natural sciences of the modern era arrived at their complex doctrines through a searching study of nature rather than through sheer speculation or abstraction from reality; that they can make inquiries into nature in a more exact way, because laboratory conditions permit phenomena to occur under controls which do not exist in nature; and finally, that a confident acceptance of the immediate evidence of the senses is nothing else than an uncritical overestimation of this somewhat crude set of organs, which can demonstrate its real vigor only in co-operation with keen and far-reaching powers of reason. One is tempted to remind the critic of the physical theory of colors of his own words — "if you despise reason and science, man's loftiest power." Let us leave alone, however, this quarrel over the theory of colors; it appears advisable to consider this quarrel from the standpoint of psychology rather than from that of natural science.

Facts gathered in connection with the phenomenon of interference helped a great deal to bring about the victory of the wave theory of light, absurd as it may seem to a mind guided solely by immediate experience. The substance of this theory can be described in this way: the addition of two brightnesses results in darkness, or, to use an equation:

light + light = dark

This phenomenon is not observed in daily life; it requires for adequate observation a special arrangement of light-rays. A theory considering light to be of material nature was unable to account for this equation, as a combination of two material particles can result only in more material, not less (Newton thought of explaining the phenomenon of interference by supposing that light-particles are equipped with special "fits"; but such an attempt at an explanation would presuppose essentially a compromise and must be rejected by a consistent wave-theory).

On the other hand, for the wave-theory the phenomenon of interference is obvious. Imagine a wave produced by the swinging of a rope attached to a flag-pole; the arrival of a wave-crest at the top of the pole will result in a shaking of the pole, and a similar shaking in the opposite direction will be produced by the arrival of a wave-trough. If we produce two waves in the rope in such a way that the crest of one and the trough of the other reach the top of the pole simultaneously, then the crest and the trough will cancel each other, and no tremor of the pole will occur. This can serve as an illustration of our equation; it can be written in the following form:

push + push = repose

The above equation of light can now be well understood, if we regard brightness as a push of a light-wave which is characterized by a double direction. A schematic representation of the interference of such cross-waves is given in Fig. 3.

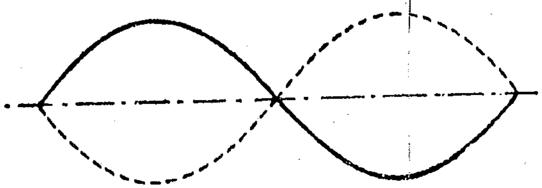

Fig. 3. The Phenomenon of Interference

The great merit of making the theory of light-waves plausible belongs to the French physicist Fresnel. He made a particular investigation of the problem of the exact nature of light-waves. There are longitudinal and transverse waves; to the latter class belong, for instance, water-waves, in which individual particles of water dance up and down and thus move transverse to the progressive direction of the wave. In longitudinal waves, on the other hand, individual particles dance back and forth in the direction of the propagation of the wave, so that a thickening and a thinning takes place as a result, and spreads forward; sound-waves exemplify this case. Fresnel was able to determine that light is connected with transverse waves, and his studies dealt primarily with the so-called polarization of light, a phenomenon characterized by the 'transverse quality' of light.

But if light has the nature of waves and is, consequently, not a substance, but a phenomenon of motion in a medium — what then is that medium itself? This is the famous question concerning ether, to which now we must give some attention. The originators of the wave-theory believed as a matter of course that the propagation of light must be conceived as a wave in a medium; and they designated this imaginary medium ether, thus availing themselves of a very old notion in natural philosophy. As a matter of fact, in all other phenomena of waves such a medium is definitely known and the necessity for it seems to be apparent. The water-wave, for instance, can come into existence only because material water particles dance up and down, so that, while each adjacent particle executes the rhythm of the movement a little later, there arises a lateral movement of the wave; this movement presents an immaterial phenomenon on a material background. Apart from such a background, wave movement appears to be unthinkable. It seems to be inseparable from the presence of matter — and this assumption is the deep source of all attempts to discover the ether of light.

However, if there is a substantial medium, it must manifest itself in other ways than in the propagation of light. We do not have to infer the existence of water from the observation of waves. There are other direct activities demonstrating to us the existence of water, such as resistence to movement or the feeling of wetness, experienced in contact with water. True enough, we should not expect such crude manifestations from ether, supposedly the finest substance permeating the pores of solid bodies. But there must be some effects demonstrating its existence; it must be possible to prove its reality by means of the finest physical instruments. In fact, the history of physics is full of most ingenious attempts to demonstrate the existence of ether and to reveal its nature. But the results, we must concede, were completely negative.

A detailed description of these experiments is out of place here, though one of them will be discussed in the next chapter. Suffice it to mention that the 'transverse' character of the light waves brings troubles in its wake, insofar as only longitudinal waves should be expected in such a fine medium. Furthermore, there arises the question of currents in ether. Similarly to water, there must arise in ether not only wave-motion but also current-motion resulting, in the vicinity of solid objects and celestial bodies, in whirlpools. The appearance of such currents should be discernible as disturbance in the propagation of light. But nothing of the kind has ever been observed. The whole mastery of optical experimentation has been used in the pursuit of some proof of the existence of ether, but all in vain: the results obtained can be accounted for only on the assumption that there is no ether.

Thus natural science found itself in a most peculiar situation. Its experiments speak against the theory of ether. What then speaks in its favor? In the last analysis, only speculative considerations compel us to accept it. However, these considerations are of extraordinarily convincing character. This is the compelling idea: if there are wave motions, there must be a medium. Thus reason is opposed to experience, and either one or the other must win in the end.

In such a conflict it is proper to subject the idea to a critical revision. There have been many ideas claiming an absolute validity and supported by the persuasive power of logical conclusions; yet they have been unable to withstand a deeper criticism. The concept of ether has not been formed on the basis of a logical conclusion, to be sure: it has an altogether different source. All common ideas comprising the knowledge of nature, such as substance, matter, wave, or motion, have not sprung out of pure speculation, but out of primary experiences of daily life. And nothing is more dangerous than to forget their origin and to ascribe to them a necessary and unconditional existence Quite on the contrary, it is important to comprehend that they have grown out of crude observations of nature, that they are hardly more than superficial generalizations concerning the world, and that it has never been demonstrated that these ideas are applicable to a finer understanding of nature.

Material substance is definitely such an idea tending to endow something highly intricate with a logically simple form. What a complicated conglomeration of matter and forces is, for instance, the substance of water! One has to think only of the atomic theory portraying it as a turmoil of individual particles attracting each other or repelling each other, sometimes mutually dependent, sometimes completely independent. A more faithful picture of the substance of water resembles a shower of bullets rather than a uniform substance. We may take it for granted that the concept of substance, characterizing this intricate picture, will do for all practical purposes. But will it do, when the explanation of the finest foundations of natural processes is at stake?

This question has to be asked, thoughtfully, only once to plant a seed of doubt in our hearts with regard to a positive answer. We should assume, on the contrary, that the concept of material substance is hardly applicable to the propagation of light, occurring both in the interspaces between the atoms and in the astronomical realm; it is a concept formed to fit the 'macroscopic' relations. If this is the case, then the natural scientists will do wisely to worry as little as possible over ether and face the possibility that there is no ether at all. In other words, there may exist an oscillating process of propagation, which is not in any sense connected with a material medium. Why should we not form this new conception conforming so much better to the experience of optics? Must we transfer, under all conditions, the 'macroscopic' ideas to 'microscopic' dimensions? May we not form, in view of highly complex and exact experiences of science, new fundamental principles doing justice to our new knowledge?

That scientific optics could and did take this path was a result of the progress made in the meantime by another physical discipline, the theory of electricity. Here we became acquainted with forces of an entirely different kind than those of mechanics familiar since earlier days; the experimental investigations of Faraday, above all, showed that, not only the electrical current flowing in the

wire, but also the electric and magnetic fields found in the air or empty space, contain in reality power and energy. One thinks of magnetic and electric lines of force in terms of iron filings, as a sort of proof; these lines manifest, with a lawfulness of their own, the existence of electric and magnetic states permeating space and penetrating bodies.

It is not necessary to regard these states as states of a special substance, like that of ether; if these fields are to be considered as substance, then it is a substance of an entirely different kind from that of material bodies, such as water and air. They lack, above all, a very important quality of matter, namely, that no two bodies can occupy one and the same space — that is, impenetrability. On the other hand, two electrical fields can be superimposed without excluding each other, for the simple reason that they do not enclose any space whatsoever. It is incorrect to retort with the statement that a similar thing is observed in the mixing of fluids or gases. As a matter of fact, such a mixing should not be understood as placing the molecules 'within each other' but rather as placing them 'alongside each other', so that every one of them encloses space according to the principle of impenetrability. Two electrical fields, however, are able to occupy one and the same space at the same time, not in the sense of mixture, but as being 'within each other', whole or part; they form together a new electrical field, in which either of the two fields can be demonstrated at any time. If the electrical fields are construed as substances, then the concept of substance unavoidably acquires an entirely new meaning; so that it is clearly advisable to retain the old idea of substance and to regard the concept of 'fields' as its opposite.

We may say, then, that the study of electricity has taught ~~us to conceive~~ materiality in a form different from substance, namely, in that of field. To this latter concept we owe the victory over the prospectless theory of material ether.

It was the Englishman James Maxwell who took the decisive step in reducing optics to phenomena of electricity. Taking Faraday's experiments as the starting point, he sought a mathematical formulation of the fundamental principles of electricity and finally presented them in the form of the famous Maxwellian equations; the result was a concatenation, i. e. a binding together, of electric and magnetic conditions as observed in the phenomena of induction (consisting in the creation of a magnetic field by means of an electrical current, or vice versa). Maxwell noticed, however, that a mathematical development of his basic principles necessarily led to the conclusion that there must be electrical vibrations spreading through space. He immediately assumed that these vibrations must be identical with light and that light is, consequently, nothing other than an electrical phenomenon similar to the electric or magnetic fields arising in the vicinity of electrical currents; the former differs from the latter merely in the extraordinarily high rate of vibrations. He himself could give no experimental proof of this mathematical theory; the proof had to await the discovery of improved methods of observation.

The confirmation of Maxwell's theory was reached along two lines. On the one hand, it became possible to show the effect of electric and magnetic fields on light-generating structures or radiant atoms (Stark's and Zeemann's effect) and thus to prove that the emission of light is essentially an electrical phenomenon. On the other hand, long before these experiments took place, there came the great discovery of Heinrich Hertz: he succeeded in producing, by means of an electrical apparatus, electric vibrations which, though of considerably lower frequency of vibration than that of light, showed properties related to it and which could spread through space by themselves and independently of wires. These electrical vibrations produced by Heinrich Hertz in his laboratory were nothing other than wireless waves, known today as radio waves. Their widespread technical use in telegraphy and radio constitutes a proof of how a discovery made purely for theoretical reasons, that is, in search of understanding natural phenomena, can yield unsuspected industrial benefit, never thought of even by the discoverer himself.

Electrical waves are advancing fields which should not be regarded as bound to a material medium. They are waves in which electricity continually alternates between positive and negative. Yet they are not dependent on the ups and downs of small material particles, but move quite independently through space. They thus have qualities found by the science of optics in the slow course of experimentation with light. We are able to say today that light is simply a train of electrical waves of high frequency.

The pursuit of this profound knowledge has yielded us an insight of unsuspected richness into a multitude of electrical waves. We have succeeded in producing electrical waves the frequency of which is by far greater than that of light. These waves of high penetrating capacity are the X-rays, discovered by Roentgen. The examination of radioactive substances has proved that they are sending out even faster vibrating and more penetrating radiation, namely, the gamma-rays related in many ways to the X-rays. Moreover, we have succeeded also in bridging the gap that previously existed between the light rays and the waves of the wireless, the progress having been made on both sides. On the one hand, the waves of the wireless telegraphy have been shortened (higher frequency means shorter waves); on the other hand, longer waves which no longer possess the property of being seen by the human

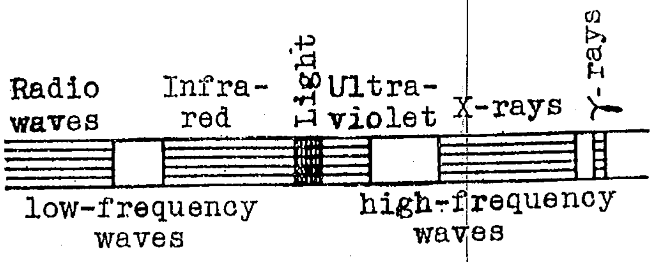

Fig. 4. The Total Spectrum

eye, have been isolated among the light rays. The totality of these waves — the so-called spectrum — is represented in the order of their wave-lengths on Fig. 4.

Thus we have come to regard light as a rather narrow section in the whole spectrum of electrical waves. There are electrical waves of every frequency, from 0 to almost any magnitude. The highest known frequencies lie in the trillions (gamma-rays). But the human eye is sensitive only to a very small stretch of frequencies called light. The eye does not respond to the waves of other frequencies, and we need complicated apparatus to get acquainted with them.

The limitation of the eye to a definite field of frequency has its source in the history of man's development. The realm of electrical waves sent by the sun appeared to the eye as light; these rays are abundantly represented on the surface of the earth and permit an exchange of action between human beings and things, which we call 'seeing'. It cannot be called impossible that our eyes may become adjusted to other waves, for instance, to those of the wireless telegraphy; but our biological organization prevents this, insofar as we cannot change our adaptation quickly — in the manner of a receiving radio-set — so as to adjust ourselves to other waves. Consequently, we avail ourselves of physical instruments, modify the action of waves with a frequency higher or lower than that of light, and finally bring about effects which our sense organs can register as visual or auditory phenomena. However, when we visualize the whole scope of electrical waves (as represented in Fig. 4) and notice the little band of rays perceptible as light, it appears to us as if the world were covered with a curtain with a small hole through which we are allowed to contemplate only a fringe of nature's immense riches.

In conclusion, one may be desirous to raise the question: But what about sound waves? The truth is that sound waves do not enter here into consideration at all. Though they are waves, they have no place in Fig. 4: for they are not electrical waves. Rather, they are elastic vibrations in a medium, with qualities similar to those formerly ascribed to light. Their 'ether' is the air; they cannot be considered as fields. They are vibrations in a substance, not unlike the waves of water. Sounds are, therefore, inseparable from a medium. The sound of an electrical bell dies in a vacuum. In small inter-atomic regions there can be no sound, as the concept of substance, essentially macroscopic, has here no application. The sound waves, as completely macroscopic phenomena, offer us a picture of how light should not be conceived. For light, by virtue of its electrical character, stems from deeper foundations than the crude substance of the corporeal waves.