THE ELEMENTS OF ASTRONOMY

A NON-MATHEMATICAL TEXTBOOK FOR USE AS AN INTRODUCTION TO THE SUBJECT IN COLLEGES, UNIVERSITIES, ETC., AND FOR THE GENERAL READER

BY

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PREFACE TO THE SECOND EDITION

The very kind reception given this book both by teachers and general readers has demonstrated that a non-mathematical text can be used to advantage in bringing to the student the facts and principles of astronomy.

Our science is changing so rapidly, and so much that is new and interesting has been published in the last two years, that a revision was necessary in order to keep the book up to date. The effort was made to include all important advances known to the end of 1927. In addition to these changes in the text additional illustrations and a new set of star charts, especially drawn for this book, have been added.

Many thanks are due those who accepted the invitation in the preface of the first edition to call attention to errors and to make suggestions. A number of changes were made as the result of the very helpful criticisms received. A similar invitation is again extended. The willingness of others to answer queries or to supply materials for illustrations is also gratefully acknowledged.

THE AUTHOR.

GOODSELL OBSERVATORY,
CARLETON COLLEGE,
May, 1928.

PREFACE TO THE FIRST EDITION

This book is the result of attempting to present the subject-matter of astronomy to a number of classes of college students, over half of whom had had no mathematics beyond one year of algebra and one year of plane geometry in high school. In consequence, very little is presented in mathematical form, but an effort has been made to develop the necessary physical concepts so that at the close of the course the student would be in possession of the main facts of the subject as well as have an elementary understanding of the principles and methods involved in modern astronomical investigation.

An effort was made to have the material represent the state of the science at the end of 1925, to the extent that it was available in publications accessible to the author. Much interesting material was of necessity omitted in order to avoid too lengthy a treatment in a first course. It is hoped, however, that no important results have been omitted.

The increasing use of the metric system has led the author to believe that the time has come to adopt it in a textbook of this character. The equivalents in the English system of units are given in parentheses after the metric values for those who do not care to make the change of systems.

Whenever possible, credit was given to the one originating an idea or beginning a new line of investigation. In many cases, however, it seemed impossible to trace matters to their sources, as so much is now common knowledge and the names of originators appear to be lost.

The author is under great obligation and hereby expresses his sincere thanks to many who have aided him in the preparation of this book. He is especially indebted to Prof. E. B. Frost for the use of the facilities of the library of the Yerkes Observatory during the summer of 1925; to his colleague, Prof. C. H. Gingrich of Carleton College, who read the entire manuscript and proof; to Prof. S. Einarsson, of the University of California, who read a portion of the manuscript and to Prof. W. F. G. Swann of Yale University for the statement of the Einstein theory of relativity

in Sec. 140. Permission to use photographic material or drawings was freely given by many. Without these fine results of modern observing the value of the book would have been greatly impaired. The source of each illustration thus obtained is given in the appropriate place.

Every effort was made to avoid errors in the manuscript, but as it is impossible to avoid all mistakes the author will appreciate having any such called to his attention, no matter how unimportant.

This book is offered by the writer to such of his fellow-teachers as care to use it, with the hope that it may be of some use in presenting the elementary facts of our great science in a form that the first-year student can comprehend. It is also offered to the general reader who may desire to have a non-mathematical treatment of the science of the stars, with the wish that it may afford him both pleasure and profit.

THE AUTHOR.

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CONTENTS

THE ELEMENTS OF ASTRONOMY

CHAPTER I

INTRODUCTION

Astronomy is the science of the heavenly bodies. These include the sun, moon, planets and satellites, comets, stars and nebulæ. The pursuit of astronomy implies not only a study of these bodies with relation to their distances, dimensions, movements, physical characteristics and the laws which govern them, but also the attempt to determine both their past and future.

1. Early Astronomy.—When man was nothing more than a savage it was necessary for him to pay some attention to astronomical occurrences, even if only to the extent of recognizing the daily return of the sun or the connection between the growth of vegetation and the seasons.

At a later stage of development he used the day, month and year as units of time, and many religious observances were timed by the position of sun or moon in the sky. There is some evidence that at least certain of the Egyptian pyramids were used in making astronomical observations and ancient temples and other places of worship were frequently oriented with respect to sun or stars.

So far as can be determined, astronomy was the first of the sciences to be developed by the ancients, and its study, without doubt, played an important part in the intellectual development of ancient peoples. Old records of the Chinese, writings on Babylonian tablets and remnants from the chronicles of the early Egyptians all show evidence of the cultivation of astronomy. They contain records of eclipses of sun and moon, the appearance of bright comets, the conjunctions of planets, etc.

Ancient navigators used the stars to guide them when they made their voyages, caravans across the deserts did likewise and the old-time shepherd or farmer was aided in his pursuits by paying attention to sun and stars.

2. Place of Astronomy among the Sciences.—Astronomy is the only one of the sciences which gives man some knowledge of the entire visible universe. Other sciences devote their attention to some one phase of the universe and play their part in getting an understanding of some of the fundamental laws governing matter and energy, but they restrict themselves, almost exclusively, to those phases of nature which are in evidence upon the earth, which is only an insignificant part of the whole. Astronomy, however, strives to unravel the secrets of nature, not only upon the earth but also throughout all space within reach of the most powerful instruments, and thus acquaints man with his immediate surroundings as well as with what is going on in regions far removed from ordinary, everyday experience and contacts. One of the goals of astronomy may be said to be to make man feel "at home" in the universe.

3. Relation of Astronomy to Other Sciences.—In pursuing as its aim the understanding of the universe, astronomy is indebted to other sciences for much of its progress. It utilizes the information gathered by the students of physics, chemistry, geology and biology as well as all the resources of mathematics. It repays the debt by unfolding to these sciences the vast laboratories in sun, stars and nebulæ, where matter is met with in a variety of forms and under conditions which cannot as yet be duplicated on the earth.

The solution of some astronomical problems has been the direct cause of some of the greatest developments in mathematics. Newton's "Principia" stands as one of the greatest products of the human intellect. It was the desire to solve the problem of the motions of the members of the solar system which led its author to produce it.

4. Practical Aspects of Astronomy.—Accurate time, land surveys, international boundaries, map making or cartography, and navigation are directly dependent upon astronomical observations.

Accurate time is one of the necessities of modern civilization. The astronomer sets his clocks by means of observations of the stars, and the official time of all civilized countries is obtained from the clocks in the astronomical observatories.

Land surveys depend upon a knowledge of true north-and-south lines. These are determined by astronomical observations and are the prime meridians upon which accurate surveys depend.

When the 49th parallel of latitude was decided upon as part of the boundary line between the United States and Canada the international commission appointed to mark this line included eminent astronomers from both countries, by whose observations of the stars the exact location was determined.

Map making depends upon an exact knowledge of the shape and the size of the earth and the locations of the meridians and parallels. This knowledge is directly dependent upon observations of the stars whose exact positions in the heavens have been determined by generations of astronomers.

The location of a ship at sea is obtained by astronomical observations and the deviations of the compass are found by comparing it with known directions in the sky. Without such knowledge modern commerce would be greatly handicapped and it is doubtful if it could be carried on successfully if this information were lacking.

It is thus evident that the modern world is greatly indebted to astronomy, which supplies it with time, directions, positions on the earth and their relationships.

Another phase of astronomy is being developed at the present time which presages vast possibilities of service to mankind. The weather and the climate of any region on the earth are largely dependent, in the last analysis, upon the heat which comes from the sun. A careful study of the heat received from this body shows that the amount undergoes minute changes from day to day and larger variations in longer periods of time. A correlation has been shown to exist between the amount of heat received at any time and the mean temperatures, several days later, at certain selected stations. This correlation is so close that it is used to forecast temperatures with considerable success. It seems possible, therefore, that in time such forecasts can be made for any place on the earth. It also seems possible that the law of variation of the sun's heat will ultimately be discovered and the heat to be received in a month or a year thus rendered capable of prediction in advance. When this shall be accomplished, long-range weather forecasts will almost certainly follow. The immense value to agriculture of the previous knowledge that a certain summer will be hot, cold, wet or dry can hardly be overestimated if the world's food supply continues to come from the land. Such a development of astronomy is as yet little more than a dream, but it does not seem wholly outside the realm of possibility.

5. Place of Astronomy in Education.—The greatest value of astronomy to the average individual at the present time lies in its appeal to the intellect. The contemplation of great worlds outside the earth; the study of the stars individually, in clusters or in vast systems; the realization that the universe is a universe of order and subject to law; the gradual discovery of the laws in accordance with which it operates and the thoughts aroused as to its origin, purpose and future development will more than repay the investment of time and effort necessary to make them possible.

To the great majority the universe is practically a sealed book. We exert ourselves through great educational systems, maintained at enormous expense, to make the student acquainted with his city, state and nation as well as with foreign lands, and we endeavor to acquaint him with the laws of nature as they operate on this small earth, so that he shall feel in touch with his environment, but, thus far, we have done very little to make him acquainted with the vast universe in which he finds himself, and we allow him to spend his entire life in ignorance of the wonderful realms outside the earth. It is important that he be acquainted with the earth and what it contains, but it seems a great mistake to keep his thoughts forever centered on this globe and not allow them to go out to the stars.

6. Subdivisions of Astronomy.—According to purpose and method, astronomy may be divided into four main branches: astrometry, practical astronomy, theoretical astronomy and astrophysics.

Astrometry deals primarily with the measurement of the positions, distances, dimensions and apparent motions of the heavenly bodies; *practical astronomy* deals with such matters as the determination of time, latitude and longitude; *theoretical astronomy* devotes itself to the mathematical study of the motions of the heavenly bodies under the influence of gravitation; and *astrophysics* deals with their physical and chemical characteristics, such as brightness, temperature, composition, magnetic properties, motion in the line of sight as determined by the spectrograph, etc. There is, however, no sharp distinction between these various parts of the subject, each being more or less connected with or dependent upon the others.

CHAPTER II

THE EARTH

All astronomical observations must be made at the earth's surface and through the earth's atmosphere. These circumstances determine, to a large extent, not only what we can learn concerning the heavens, but also the methods which must be employed in studying them. It is therefore necessary to learn something about the earth before we can study the rest of the universe to the best advantage.

7. Facts Concerning the Earth.—The following facts may be stated concerning the earth, and then each one will be examined more in detail:

1. The earth is an oblate spheroid having a polar diameter of 12,714 km (7900 miles) and an equatorial diameter of 12,757 km (7927 miles). The mean diameter is 12,742 km (7918 miles).

2. Its mass is equal to 6×10^{21} metric tons (6.6×10^{21} short tons) and its mean density is about 5.5 times that of water.

3. The earth rotates on its axis once in 24 sidereal hours in a direction from west to east.

4. The earth revolves about the sun at a mean distance of 149,500,000 km (92,900,000 miles) once a year. This revolution is from west to east. Its orbital velocity is about 30 km (18.5 miles) per second.

8. The Earth's Shape.—Mankind, with few exceptions, seems always to have held the belief that the earth is approximately flat, and it was not until Magellan's ships actually sailed around it that the age-long belief was shattered and the rotundity of the earth accepted as a fact.

Another of the elementary proofs that the earth is at least approximately spherical can be obtained by observing eclipses of the moon. No matter how the moon moves into or out of the shadow of the earth, the edge of the shadow is always seen to be bounded by an arc of a circle (Fig. 1).

Another proof of its approximate shape is that when a vessel is observed going out to sea the hull vanishes first, the superstructure next and the smoke from its fires last.

The exact shape is determined by the principles described in Secs. 9 and 13.

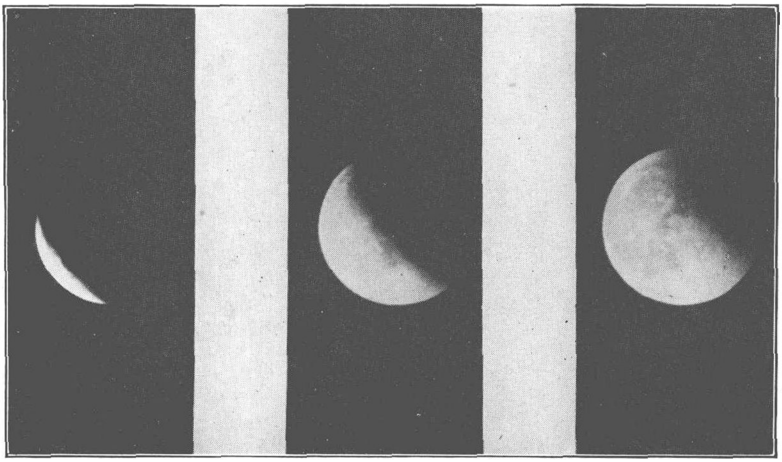

FIG. 1.—Partial phases of a lunar eclipse showing boundary of earth's shadow to be an arc of a circle. *(Photographed by Barnard of the Yerkes Observatory.)*

9. The Earth's Dimensions.—The exact dimensions of the earth are obtained by measurement. The process is termed *triangulation* because it depends upon a network of triangles, and is indicated in principle in Fig. 2.

Suppose it is desired to determine the distance between two points, *A* and *G*, so far apart that one can not be seen from the other nor both from a single intermediate point. First a distance *AC* is measured with great exactness. This is termed a base-line. Then, after selecting a point *B*, the angles *A*, *C* and *B* in the triangle are measured by a surveyor's transit or similar instrument. In the triangle *ACB* one side, *AC*, and the three angles are known, so that the other two sides can be computed by trigonometry. Another point, *E*, is then selected which is visible from *B* and *C*. Having computed *CB* and measured the angles at *C*, *B* and *E* in the triangle *CBE*, it is, in turn, possible to compute the length *EB*. This process is continued until the final triangle *EFG* is solved. In the triangle *CEG* we now know *CE*, *EG* and the angle *CEG* so that *CG* can be computed. Then in the triangle CGA we know CG, CA and the angle ACG, so that we are in a position to compute AG, the distance required.

In this statement it has been assumed that all the triangles lie in the same plane. Because of the curvature of the earth's surface it is evident that this is not actually the case, although

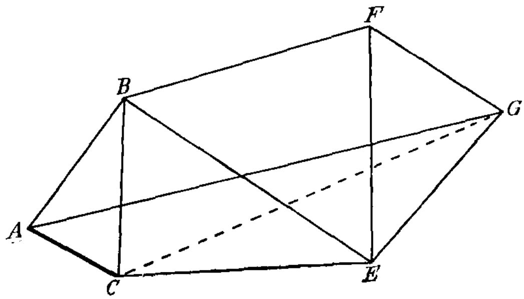

FIG. 2.—The principle of determining the distance between two points, A and G, by triangulation.

each triangle may be considered a plane triangle unless very large. This complicates the problem, but the principle used is the same.

Many such lines have been measured in this manner in various countries. It is evident that such a network of lines of known length, used in connection with the known longitudes and latitudes of the places connected, enables us to know the dimensions of the earth with great accuracy.

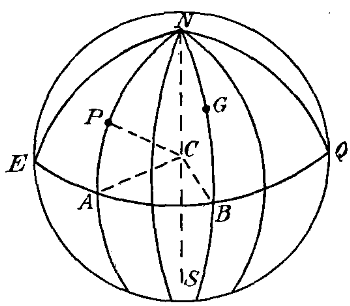

FIG. 3.

10. Longitude.—From a study of geography we are familiar with the terms *longitude* and *latitude.* We say that if we assume a series of imaginary lines, meridians, drawn from the north to the south pole of the earth (Fig. 3), and designate a certain meridian, such as NGS, as the zero meridian, then the longitude of a point P is the angle which the meridian through P makes with this zero meridian, namely, the angle PNG. We also know from the geometry of the problem that the angle PNG is equal to the angle ACB subtended at the center of the earth by that part of the equator between the two meridians. Longitude is measured east and west from the meridian through Greenwich, England.

11. Plumb-lines and Level Lines.—If a plumb-line is hanging freely, its position with respect to the earth is determined by the direction of gravity. The direction of the plumb-line is usually determined by first leveling an instrument by means of delicate spirit levels and then turning off an angle of 90° in a vertical plane. A level surface is perpendicular to the direction of the plumb-line at any point.

If the surface of the ocean were not disturbed by waves and tides it would be a level surface. A level surface therefore is not a plane but a curved surface. Similarly, a level line is not a straight line but a curved line which follows the curvature of a level surface.

12. Latitude.—There are three kinds of latitude: astronomical, geographic and geocentric.

1. *Astronomical latitude* is defined as the angle between the direction of the plumb-line and the plane of the earth's equator. If the earth were a homogeneous sphere without rotation the plumb-line would point toward its center, but, as we shall see later on, the earth is not an exact sphere and it is evident to everyone that matter is not uniformly distributed at the surface at any rate, for in some places we have a water surface and in others there are mountains. This lack of uniformity in the distribution of matter at the earth's surface, as well as any lack of uniformity within the body of the earth, will make the direction of the plumb-line slightly different on the rotating earth from what it would be if these inequalities of surface, etc. were not present. This effect on the plumb-line is called the *station error*. In Hawaii station errors up to 67″ have been noted. The method of determining station error is somewhat beyond the scope of this book.

2. *Geographic latitude* is the astronomical latitude corrected for station error. It is the latitude used in the drawing of maps.

3. *Geocentric latitude* is the angle at the center of the earth between the line drawn from the center to the point on the surface and the plane of the equator. Thus, in Fig. 3 the angle PCA is the geocentric latitude of the point P.

The greatest difference between geographic and geocentric latitude occurs at 45°, where it amounts to 11′.6. Geocentric latitude is used when results calculated for the earth's center must be changed to a point of observation at the surface, and *vice versa*.

13. Length of a Degree of Latitude.—In traveling along a meridian from the equator toward a pole it is found that it is necessary to travel a little further for each change of 1° in latitude. This means that the curvature of the earth's surface is greatest at the equator and that it becomes less the nearer we approach the poles. This is illustrated in Fig. 4. Each line drawn toward the interior is perpendicular to the tangent at the point of the curve from which it is drawn, and is therefore the direction of the plumb-line at the surface. The angles between adjacent lines are all equal. It is therefore evident that the arc of the meridian between adjacent lines at the pole is greater than at the equator, or that a degree of latitude increases in length as one goes away from the equator. Measurements of arcs of meridians by trian-

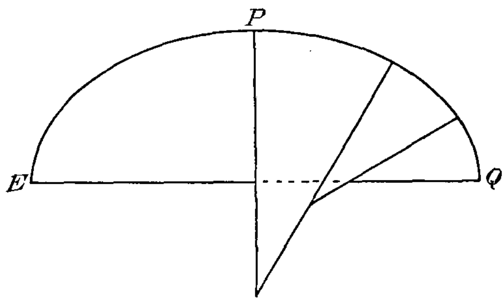

Fig. 4.

gulation in various parts of the earth have shown the following values for the length of 1° of astronomical latitude:

	Kilometers	Miles
At equator	110.55	68.71
At 45°	111.12	69.06
At 90°	111.68	69.41

Arcs of longitude along parallels have also been measured, and it is found that these are essentially uniformly curved at any particular latitude.

From these results we reach the conclusion that the earth becomes flatter the nearer we approach the poles, so that the actual shape of the earth is that of an oblate spheroid with a polar radius of 6356.91 km (3949.99 miles) and an equatorial radius of 6378.39 km (3963.34 miles).

14. The Variation of Latitude and Longitude.—Many years ago the question was raised whether the possible shifting of masses within the earth, the denudation of the continents and even seasonal changes might not produce a sufficient change in the position of matter within or on the earth to have an appreciable effect on the position of the axis of rotation with respect to the body of the earth. This change in the axis of rotation would show itself in changes in the latitudes and longitudes of places on the earth.

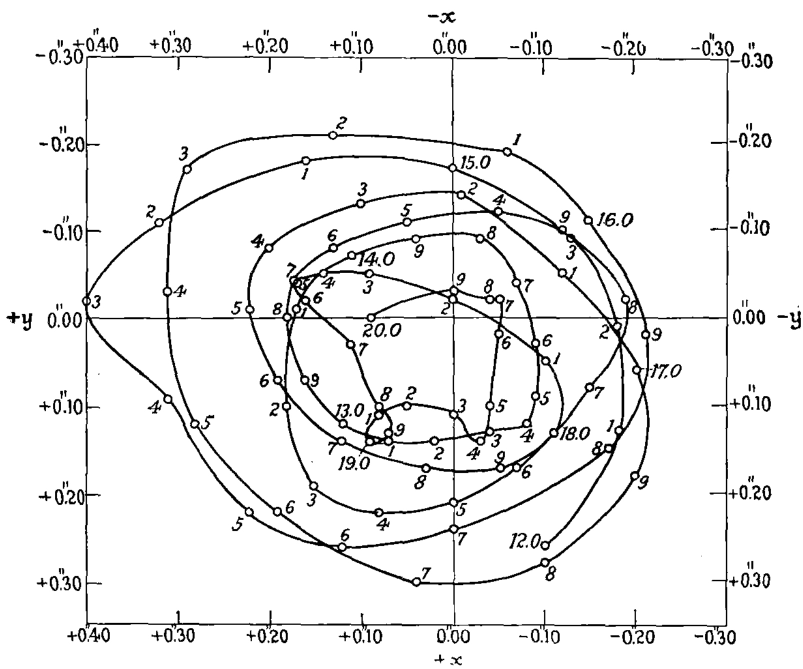

FIG. 5.—The motion of the north pole of the earth from 1912 to 1920. (*According to Wanach.*)

In 1888, Küstner published a series of observations made in 1884 and 1885 at Berlin, in which he showed that variation in the latitude of the Berlin Observatory had occurred in the course of the observations. During the same period Chandler at Cambridge, Mass., had shown that a variation existed in the measures of the latitude of the Harvard Observatory. Küstner's results led to special test observations at Berlin, Potsdam, Prague and Strassburg in 1889, which showed such accordant results that the problem was attacked by the International Geodetic Institute and for a long series of years observations were made at selected stations, mostly in the northern hemisphere. Some of these stations are still in operation. The results obtained show clearly that the rotation axis is not fixed with respect to the earth but is moving about a mean position. Another way of expressing this fact is to say that the poles wander about within a small area on the surface of the earth. Figure 5 shows the motion of the north pole of the earth from 1912 to 1920. The figure is taken from the report of Wanach in *Astronomische Nachrichten*.

It is evident that if the poles change their positions the meridians which join the poles must also be in motion. In consequence, there will be slight changes in the longitudes of places on the earth as well as changes in the latitudes.

15. The Mass of the Earth.—The *mass* of a body is usually defined as the amount of matter it contains. The word "mass" must not be confused with the word "weight." The weight of a body is a measure of the gravitational effect of the earth upon the mass of the body and this varies inversely as the square of the distance of the body from the center of the earth (Sec. 130). Thus a mass of 1 kg would weigh 1 kg at the earth's surface, but if the weighing took place at a point whose distance from the earth's center is equal to two radii of the earth its weight would be but ¼ kg if a spring balance were used. The amount of matter in the object, however, is the same—1 kg.

The first attempt to determine the mass of the earth was made by the English astronomer, Maskelyne, in 1774. His method was the following:

In Scotland there is a mountain Schehallien. By observing the direction of the vertical (plumb-line) on either side of the mountain (Fig. 6) it was possible to determine how much the mass of the mountain deflected the plumb-line. By surveys and borings it was possible to determine the mass of the mountain. Then, knowing the distance to the center of mass of the mountain and the distance to the center of the earth, it was possible to compare the gravitative effect of the earth with that of the mountain and thus determine the mass of the earth.

The modern method of the torsion pendulum, while somewhat similar in principle, is capable of producing far more accurate results and is therefore more reliable than the mountain method. A light rod is suspended horizontally by means of a fine fiber and a small ball of some heavy substance like gold or platinum is