H_2O and triclinic red crystals with 14 H_2O), various silicotungstates (5), borotungstates, and metatungstates (6).

During World War I, Copaux was assigned to the Patent Office, as head of the Chemical Department. He developed a process for the rapid preparation of phosphoric acid (7). In 1919 Copaux perfected a method for obtaining beryllium oxide (8) from beryl that, since it greatly facilitates the separation of impurities, is still the basis for the industrial production of beryllium: by treating beryl with sodium fluosilicate at 850°C., one obtains sodium fluoberyllate, which is soluble to the extent of twenty-eight grams per liter in boiling water; sodium fluoaluminate is only slightly hydrolyzed.

From 1925, Copaux continued to direct the laboratory experiments of his young collaborators on active hydrogen (9), beryllium and the heat of formation of beryllium oxide (10), and beryllium chloride, while assuming his new pedagogical and administrative responsibilities.

Several chapters of the *Traité de chimie minérale,* edited by Moissan (1904), were written by Copaux, who also published two works intended especially for students: *Introduction à la chimie générale* (1919) and *Chimie minérale* (1925), the latter with the collaboration of M. H. Perperot.

Copaux belonged to several French chemical and mineralogical societies. He was made a knight of the Legion of Honor in 1923 and an officer in 1933.

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The following abbreviations are used in the listing of Copaux's works cited in the text: *ACP, Annales de chimie et de physique; BSC, Bulletin de la Société chimique de France; BSM, Bulletin de la Société française de minéralogie;* and *CR, Comptes rendus hebdomadaires des séances de l'Académie des sciences.*

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8. "Méthode de traitement du béryl pour en extraire l'oxyde du béryllium," in *CR,* **168** (1919), 610.

9. "Quelques expériences sur la production de l'hydrogène actif," in *BSC,* **37** (1925), 141.

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ANDRÉ COPAUX

COPE, EDWARD DRINKER (*b.* Philadelphia, Pennsylvania, 28 July 1840; *d.* Philadelphia, 12 April 1897), *paleontology, zoology, natural history.*

For a detailed study of his life and work, see Supplement.

COPERNICUS, NICHOLAS (*b.* Torun, Poland, 19 February 1473; *d.* Frauenburg [Frombork], Poland, 24 May 1543), *astronomy.*

The founder of modern astronomy lost his father in 1483, when he was only a little more than ten years old. Fortunately his maternal uncle stepped into the breach, so that Copernicus was able to enter the University of Cracow in 1491. His own evaluation of his intellectual indebtedness to that institution was publicly reported as follows, at the very time that the end product of his life's work was in the process of being printed:

> The wonderful things he has written in the field of mathematics, as well as the additional things he has undertaken to publish, he first acquired at our university [Cracow] as his source. Not only does he not deny this (in agreement with Pliny's judgment that to name those from whom we have benefited is an act of courtesy and thoroughly honest modesty), but whatever the benefit, he says that he received it all from our university.[1]

Through the influence of his uncle, who had become the bishop of Varmia (Ermland), Copernicus was elected a canon of the cathedral chapter of Frombork (Frauenburg), whose members enjoyed an ample income throughout their lives. In 1496 Copernicus enrolled in the University of Bologna, officially as a student of canon law; but privately he pursued his interest in astronomy, making his earliest recorded observation on 9 March 1497. On 6 November 1500 he observed a lunar eclipse in Rome, where "he lectured on mathematics before a large audience of students and a throng of great men and experts in this branch of knowledge."[2]

On 27 July 1501 he attended a meeting of his chapter, which granted him permission to return to Italy for two more years in order to study medicine: "As a helpful physician he would some day advise our most reverend bishop and also the members of the chapter."[3] For his medical studies Copernicus chose Padua, but he obtained a doctoral degree in canon law from the University of Ferrara on 31 May 1503. Returning soon thereafter to Varmia, he spent the remaining forty years of his life in the service of his chapter.

On 31 March 1513 he bought from the chapter's workshops 800 building stones and a barrel of lime for the purpose of constructing a roofless little tower, in which he deployed three astronomical instruments. He used the parallactic instrument mainly for observing the moon; the quadrant for the sun; and the astrolabe, or armillary sphere, for the stars.

He wrote the first draft of his new astronomical system, *De hypothesibus motuum coelestium a se constitutis commentariolus,* before 1 May 1514 and discreetly circulated a few manuscript copies among trusted friends. The date is that of the catalog of a Cracow professor's books, which included a "manuscript of six leaves expounding the theory of an author who asserts that the earth moves while the sun stands still."[4] This professor was unable to identify the author of this brief geodynamic and heliostatic manuscript because Copernicus, with his customary prudence, had deliberately withheld his name from his *Commentariolus.* But a clue to the process by which his *Commentariolus* found its way into the professor's library is provided by Copernicus' statement that he reduced all his calculations "to the meridian of Cracow, because . . . Frombork . . . where I made most of my observations . . . is on this meridian [actually, Frombork lies about 1/4° west of Cracow], as I infer from lunar and solar eclipses observed at the same time in both places."[5] Furthermore, "as is clear from [lost] letters written with his own hand, Copernicus conferred about eclipses and observations of eclipses with Cracow mathematicians, formerly his fellow students."[6]

In his *Commentariolus,* Copernicus challenged the astronomical system which had dominated Western thought since the days of Aristotle and Ptolemy. Whereas these two revered authorities and their innumerable followers down through the ages insisted on centering the cosmos around the earth, Copernicus proclaimed that "the center of the earth is not the center of the universe,"[7] in which position he stationed the sun. Against the geocentrists' denial of all motion to the earth, the *Commentariolus* treated "the earth's immobility as due to an appearance."[8] The apparent daily rotation of the heavens results from the real diurnal rotation of the earth. The apparent yearly journey of the sun through the ecliptic is caused by the earth's real annual revolution about the sun. The apparent alternation of retrograde and direct motion in the planets is produced by the earth's orbital travel.

"We revolve about the sun like any other planet."[9] These portentous words in Copernicus' *Commentariolus* assigned to the earth its rightful place in the cosmos. Yet Copernicus laid no claim to priority in this respect (or in any other, since he trod with caution over very dangerous ground). In the compact *Commentariolus* he briefly recalled that in antiquity the Pythagoreans had asserted the motion of the earth. He later identified two of these Pythagoreans when, in June 1542, he wrote that stirring plea for freedom of thought which serves as the dedication of his *De revolutionibus orbium coelestium* (*Revolutions of the Heavenly Spheres*). Therein he named Philolaus as having believed in the earth's revolution (not around the sun, but around an imaginary central fire) and Ecphantus as having attributed to the earth an axial rotation (unaccompanied by orbital revolution).

Copernicus carefully refrained from linking Aristarchus with the earth's motion. He did not hesitate to cite an (unhistorical) determination of the obliquity of the ecliptic by Aristarchus (whom he was misled into confusing with Aristyllus) as 23°51′20″, equal to Ptolemy's.[10] He also reported an equally unhistorical measurement of the length of the tropical year by Aristarchus (again confused with Aristyllus) as exactly $365^d 6^h$.[11] But the passage in which Copernicus originally associated Aristarchus with Philolaus' advocacy of a moving earth was deleted by Copernicus before he released his *De revolutionibus* for publication.[12] In like manner, Ptolemy's discussion of geodynamism conspicuously omitted the name of Aristarchus, who is nevertheless cited in the *Syntaxis mathematica* in connection with the length of the year.[13] Copernicus had no desire to inform or remind anybody that the fervently religious head of an influential philosophical school had "thought that the Greeks ought to bring charges of impiety against Aristarchus."[14] The latter's superb technical achievements in astronomy were not in question. His geocentric treatise *On the Sizes and Distances of the Sun and Moon* has survived intact; but his account of the heliocentric system has perished, leaving only a trace of the first such statement in the history of mankind.

According to that pioneering declaration, "the sphere of the fixed stars . . . is so great that the circle in which Aristarchus assumes the earth to revolve has the same ratio to the distance of the fixed stars as the center of a sphere has to its surface."[15] Archimedes, who preserved Aristarchus' heliocentric conception by summarizing it in his *Sand-Reckoner,* objected as a mathematician that "since the center of a sphere has no magnitude, neither can it be thought to have any ratio to the surface of the sphere."[16] Accordingly, Archimedes interpreted Aristarchus to mean that the ratio earth : distance earth–sun = distance earth–sun : distance earth–stars. Whatever the defects in Aristarchus' formulation, he unquestionably intended to emphasize the enormous remoteness of the stars.

This fundamental consequence of heliocentrism was expressed in Copernicus' *Commentariolus* by the following inequality: distance earth–sun : distance sun–stars $<$ earth's radius : distance earth–sun. This disproportion is in fact so great that the distance earth–sun is "imperceptible" in comparison with the distance earth–stars or sun–stars.[17] The latter distance measured the size of Copernicus' universe from the sun at its center to the stars at its outermost limit.

Because he abandoned the geocentrism of his predecessors, he likewise had to enlarge the dimensions of their limited cosmos:

> Lines drawn from the earth's surface and center [to a point in the firmament] must be distinct. Since, however, their length is immense in relation to the earth, they become like parallel lines. These appear to be a single line by reason of the overwhelming distance of their terminus, the space enclosed by them becoming imperceptible in comparison with their length. . . . This reasoning unquestionably makes it quite clear that, as compared with the earth, the heavens are immense and present the aspect of an infinite magnitude, while on the testimony of the senses the earth is related to the heavens as a point to a body, and a finite to an infinite magnitude.[18]

On the basis of both reason and sense experience, Copernicus' heavens "present the aspect of an infinite magnitude."

> But it is not at all certain how far this immensity extends. At the opposite extreme are the smallest, indivisible bodies called "atoms." Being imperceptible, they do not immediately constitute a visible body when they are taken two or a few at a time. But they can be multiplied to such an extent that in the end there are enough of them to combine in a perceptible magnitude. The same may be said also about the position of the earth. Although it is not in the center of the universe, nevertheless its distance therefrom is still insignificant, especially in relation to the sphere of the fixed stars.[19]

When Copernicus' atoms are combined in sufficient quantities, they form a visible object. In like manner, when Copernicus' distance sun–earth is multiplied often enough, the product is Copernicus' distance sun–stars. Whether that distance was finite or infinite, Copernicus declined to say. Regarding the universe's "limit as unknown and unknowable," he preferred to "leave the question whether the universe is finite or infinite to be discussed by the natural philosophers."[20]

Had Copernicus elected to extricate himself from this perennial cosmological dilemma by voting for infinity, he would have had to surrender the sun's centrality, since of course the infinite can have no center. On the other hand, had he retained the limited dimensions of the traditional cosmos, the yearly orbit of his moving earth should have produced an annual parallax of the stars. This perspective displacement is in fact so minute that mankind had to wait nearly three centuries for telescopes sensitive enough to detect it. Copernicus' solution, therefore, was to impale himself on neither horn of the dilemma by declaring the universe to be "similar to the infinite."[21] The qualification "similar" permitted him to regard the universe as capable of possessing a center, while the similarity to the infinite explained the naked eye's inability to perceive annual stellar parallax.

If Copernicus hoped to gain acceptance for his revival of the concept of a moving earth, he had to overcome the ancient objections to such motion. Earth was traditionally regarded as one of the four terrestrial or sublunar elements, the other three being water, air, and fire, whereas the heavenly bodies consisted of a fifth element. Aristotle's theory of the motion of these five elements was summarized by Copernicus as follows:

> The motion of a single simple body is simple; of the simple motions, one is straight and the other is circular; of the straight motions, one is upward and the other is downward. Hence every simple motion is either toward the middle, that is, downward; or away from the middle, that is, upward; or around the middle, that is, circular. To be carried downward, that is, to seek the middle, is a property only of earth and water, which are considered heavy; on the other hand, air and fire, which are endowed with lightness, move upward and away from the middle. To these four elements it seems reasonable to assign rectilinear motion, but to the heavenly bodies, circular motion around the middle.[22]

Copernicus had transferred the earth to the category of the heavenly bodies, to which circular motion around the middle could be reasonably assigned. Yet some parts of the earth undeniably "sink of their own weight," while "if any part of the earth is set afire, it is carried from the middle upwards."[23] Such

> rectilinear motion, however, overtakes things which leave their natural place or are thrust out of it or quit it in any manner whatsoever. . . . Whatever falls moves slowly at first, but increases its speed as it drops. On the other hand, we see this earthly fire . . . after it has been lifted up high, slacken all at once. . . . Circular motion, however, always rolls along uniformly, since it has an unfailing cause. But rectilinear motion has a cause that quickly stops functioning. When rectilinear motion brings bodies to their own place, . . . their motion ends.[24]

Retaining Aristotle's doctrine that every body has its natural place in the universe, Copernicus confined the application of this principle to the displaced parts of the earth, which were subject to the sort of motion classified by Aristotle as violent. Copernicus' planet earth as a whole, on the other hand, possessed perpetual motion, natural to the heavenly bodies. This circular motion was shared by any portion of the earth temporarily detached from it: "The motion of falling and rising bodies in the framework of the universe is twofold, being in every case a compound of straight and circular. . . . Hence, since circular motion belongs to wholes, but parts have rectilinear motion in addition, we can say that circular subsists with rectilinear as animal does with sick."[25] Taken as a whole, earth has only circular motion and no rectilinear motion, just as a healthy animal has no sickness. But a loose portion of the earth has rectilinear motion conjoined with circular motion, just as a diseased beast unites sickness with its animal nature.

The three conventional classes of motion, therefore, do not correspond to entirely separate physical states. "Aristotle's division of simple motion into three types, away from the middle, toward the middle, and around the middle, will be construed as merely an exercise in logic."[26] Similarly, in geometry "we distinguish the point, the line, and the surface, even though one cannot exist without another, and none of them without body."[27]

Besides reinterpreting the traditional theory of motion to fit the requirements of his moving earth, Copernicus endowed the planet earth, as opposed to its disjointed parts, with natural, not violent, motion. Ptolemy had contended that the earth's axial rotation

> would have to be exceedingly violent and its speed unsurpassable to carry the entire circumference of the earth around in twenty-four hours. But things which undergo an abrupt rotation seem utterly unsuited to gather bodies to themselves, and seem more likely, if they have been produced by combination, to fly apart unless they are held together by some bond. The earth would long ago . . . have burst asunder . . . and dropped out of the skies.[28]

Ptolemy's anxiety was answered by Copernicus:

> What is in accordance with nature produces effects contrary to those resulting from violence. For, things to which force or violence is applied must disintegrate and cannot long endure, whereas that which is brought into existence by nature is well ordered and preserved in its best state. Therefore Ptolemy has no cause to fear that the earth and everything earthly will be disrupted by a rotation created through nature's handiwork, which is quite different from what art or human intelligence can contrive.[29]

Ptolemy was further concerned that "living creatures and any other loose objects would by no means remain unshaken. . . . Moreover, clouds and anything else floating in the air would be seen drifting always westward," since the earth's axial rotation whirls it round swiftly eastward.[30] In reply Copernicus asked:

> With regard to the daily rotation, why should we not admit that the appearance is in the heavens and the reality in the earth? . . . Not merely the earth and the watery element joined with it have this motion, but also no small part of the air. . . . [The reason may be] either that the nearby air, mingling with earthy or watery matter, conforms to the same nature as the earth, or that [this] air's motion, acquired from the earth by proximity, shares without resistance in its unceasing rotation.[31]

By contrast with the upper layers of air, the lower layers are firmly attached to the earth and rotate with it. This partnership answers the argument that "objects falling in a straight line would not descend perpendicularly to their appointed place, which would meantime have been withdrawn by so rapid a movement" as the earth's rotation.[32] Pro-Copernicans and anti-Copernicans later conducted experiments to determine whether an object dropped vertically from a height, stationary or moving with respect to the earth's surface, fell precisely at the foot of the height. The divergent results of these numerous trials were variously interpreted; and decisive experimental confirmation of the earth's daily rotation was first provided by Foucault's pendulum in 1851, not long after Bessel, F. G. W. Struve, and T. Henderson published their independent discoveries of annual stellar parallax as direct observational proof of the earth's yearly orbital motion.

In addition to the diurnal rotation and annual revolution, Copernicus felt obliged to ascribe to the earth what he called its "motion in declination."[33] When prolonged, the axis about which our planet rotates daily meets the firmament at the celestial poles. Midway between these poles lies the celestial equator, the intersection of the plane of the earth's equator and the celestial sphere. In performing its annual revolution around the sun, the earth describes what Copernicus termed the "grand circle," the plane of which cuts the celestial sphere in the ecliptic. The poles of the ecliptic are the end points of the axis of the earth's orbital revolution. The plane of that revolution, or ecliptic, is inclined to the celestial equator at an angle known as the obliquity of the ecliptic. As Copernicus said in the *Commentariolus,* "The axis of the daily rotation is not parallel to the axis of the grand circle, but is inclined to it at an angle that intercepts a portion of a circumference, in our time about 23 1/2°."[34]

In Copernicus' time a spherical body revolving in an orbit was considered to be attached inflexibly to the orbit's center, as though from this hub a rigid spoke ran right through the revolving ball. Therefore, if the earth were subject only to the diurnal rotation and annual revolution without the third motion in declination,

> no inequality of days and nights would be observed. On the contrary, it would always be either the longest or shortest day or the day of equal daylight and darkness, or summer or winter, or whatever the character of the season, it would remain identical and unchanged. Therefore the third motion in declination is required. . . . [The motion in declination] is also an annual revolution but . . . it occurs in the direction opposite to that of the [orbital] motion of the [earth's] center. Since these two motions are opposite in direction and nearly equal [in period], the result is that the earth's axis and . . . equator face almost the same portion of the heavens, just as if they remained motionless.[35]

The function of Copernicus' third motion in declination was to keep the earth presenting a virtually unchanging aspect to an observer viewing it from a distant star, whereas to a spectator stationed on the sun it would constantly pass through its cyclical seasonal changes. Without the motion in declination Copernicus' earth would always look the same as seen from the sun, while its axis of rotation would describe a huge conical surface in space instead of pointing toward the vicinity of the same star.

The rotational axis, however, is not directed toward precisely the same star because

> the annual revolutions of the center and of declination are nearly equal. For if they were exactly equal, the equinoctial and solstitial points as well as the entire obliquity of the ecliptic would have to show no shift at all with reference to the sphere of the fixed stars. But there is a slight variation, which was discovered only as it grew larger with the passage of time.[36]

This slight variation, the precession of the equinoxes, had been explained by Ptolemy as due to a slow eastward rotation of the sphere of the stars. But that sphere had to remain absolutely motionless in the cosmos of Copernicus, who had replaced the apparent daily rotation of the stars by the real axial rotation of the earth.

In like manner, for Ptolemy's motion of the starry sphere in 36,000 years, Copernicus substituted the behavior of the earth:

> [Its] two revolutions, I mean, the annual declination and [the orbital motion of] the earth's center, are not exactly equal, the declination being of course completed a little ahead of the period of the center. Hence, as must follow, the equinoxes and solstices seem to move forward. The reason is not that the sphere of the fixed stars moves eastward, but rather that the equator moves westward.[37]

Whereas modern astronomy has adopted Copernicus' account of precession, its rate eluded him. The modern constant value, about 50″ a year, was regarded by him as the mean rate of precession: he was misled by his predecessors' divergent determinations of this minute quantity into believing that it underwent a cyclical variation. He likewise made the same error regarding the obliquity of the ecliptic. The available evidence warranted only the conclusion that the obliquity diminished progressively. Nevertheless, he supposed that after decreasing from a maximum of 23° 52′ before Ptolemy's time to a minimum of 23° 28′ after his own time, it would then reverse itself and increase to its previous maximum, oscillating thereafter in a 24′ cycle of long period.

The sun appears to move with annually recurring variations of speed along its course in the ecliptic, thereby making the four seasons unequal in length. To represent these phenomena, Ptolemy had the sun traverse a circle whose stationary center was separated by some distance from the earth. This eccentric circle's apogee, or point at which the sun attained its greatest distance from the earth, was regarded by Ptolemy as fixed in relation to the stars at 24° 30′ before the summer solstice. Al-Battānī located the apogee only 7° 43′ before the summer solstice.[38] "In the 740 years since Ptolemy it advanced nearly 17°."[39] Al-Zarqālī, however, "put the apogee 12° 10′ before the solstice."[40] Thus,

> in 200 years it retrogressed 4° or 5°. Thereafter until our age it moved forward. The entire period [from Ptolemy to Copernicus] has witnessed no other retrogression nor the several stationary points which must intervene at both limits when motions reverse their direction. [The absence of] these features cannot possibly be understood in a regular and cyclical motion. Therefore many astronomers believe that some error occurred

> in the observations of those men [al-Battānī and al-Zarqālī]. Both were equally skillful and careful astronomers so that it is doubtful which one should be followed. For my part I confess that nowhere is there a greater difficulty than in understanding the solar apogee, where we draw large conclusions from certain minute and barely perceptible quantities. . . . As can be noticed in the general structure of the [apogee's] motion, it is quite probably direct but nonuniform. For after that stationary interval from Hipparchus to Ptolemy the apogee appeared in a continuous, regular, and accelerated progression until the present time. An exception occurred between al-Battānī and al-Zarqālī through a mistake (it is believed), since everything else seems to fit.[41]

Copernicus still believed in the fixity of the earth's aphelion, or—its Ptolemaic counterpart—the solar apogee, when he composed the *Commentariolus* between 15 July 1502 and 1 May 1514. Later, in writing book III of *De revolutionibus,* where he took into account the related work of the Arab astronomers, he made the terrestrial aphelion move. But, the observations of al-Battānī and al-Zarqālī being discordant, he was "doubtful which one should be followed." By the summer of 1539, when his disciple Rheticus drafted the *Narratio prima* (*First Report*) of the Copernican system to be presented in printed form to the reading public, both al-Battānī and al-Zarqālī were suspect in Copernicus' mind. In creating his model for the progressive motion of the earth's aphelion, Copernicus felt justified in lowering al-Battānī's determination by 6° and raising al-Zarqālī's by 4°.

> Now you see [says Rheticus] what great effort my teacher had to put forth to determine the mean motion of the [solar] apogee. For nearly forty years in Italy and here in Frombork, he observed eclipses and the [apparent] motion of the sun. He selected the observation by which he established that in A.D. 1515 the solar apogee was at 6 2/3° of Cancer [= 6 2/3° after the solstice]. Then examining all the eclipses in Ptolemy and comparing them with his own very careful observations, he concluded that the mean annual motion of the apogee with reference to the fixed stars was about 25″. . . .[42]

In his earliest recorded observation, made in Bologna after sunset on 9 March 1497, Copernicus reported an occultation of Aldebaran by the moon. In his *De revolutionibus* he used this observation to support his computation of the lunar parallax.[43] The variation in this quantity and in the length of the moon's apparent diameter was greatly exaggerated in Ptolemy's lunar theory, as Copernicus emphasized in the *Commentariolus:*

> The consequence by mathematical analysis is that when the moon is in quadrature, and at the same time in the lowest part of the epicycle, it should appear nearly four times greater (if the entire disk were luminous) than when new and full, unless its magnitude increases and diminishes in no reasonable way. So too, because the size of the earth is sensible in comparison with its distance from the moon, the lunar parallax should increase very greatly at the quadratures. But if anyone investigates these matters carefully, he will find that in both respects the quadratures differ very little from new and full moon. . . .[44]

Mounting the moon on an epicycle whose deferent was not concentric with the earth, Ptolemy and his followers had the epicycle's center traverse equal arcs in equal times as measured from the earth's center. While Copernicus' predecessors "declare that the motion of the epicycle's center is uniform around the center of the earth, they must also admit that it is nonuniform on its own eccentric, which it describes."[45] Such a model was rejected by the *Commentariolus* as conflicting with "the rule of absolute motion," according to which "everything would move uniformly about its proper center."[46] This principle was violated a second time in the Ptolemaic lunar theory, which had the moon traverse equal arcs on its epicycle, as measured not from the epicycle's center but from a different point known as the equant or the equalizing point.

In order to avoid using an equant, which he regarded as an impermissible device, in his own lunar theory Copernicus obtained an equivalent result by piling on the traditional epicycle a second, smaller epicyclet carrying the moon. This method of adhering to the axiom of uniform motion, at the same time eliminating the equant and the excessive variation in the length of the moon's apparent diameter, had been adopted in the Muslim world by Ibn al-Shāṭir about a century before Copernicus was born. Was Copernicus aware of the work done by his Damascene predecessor? The latter introduced a second epicycle for the sun too, but Copernicus did not follow suit. He used eccentric models, which had been rejected by Ibn al-Shātir. His numerical results also differed, being based in part on his own observations. Since he knew no Arabic and Ibn al-Shāṭir's manuscript had not been translated into any language understood by Copernicus, presumably he had no direct acquaintance with the Muslim's thinking. Their conclusions, independently reached, strikingly converged on the same theoretical and practical shortcomings in Ptolemaic astronomy. But there is no inkling of geodynamism in Ibn al-Shāṭir.

The same cannot be said about Ibn al-Shāṭir's contemporary, Nicole Oresme, who around 1377 made the first translation of Aristotle's *De caelo* into a modern language. In his commentary Oresme considered many arguments concerning the diurnal rotation, which should more reasonably, it seemed to him, be assigned to the earth. Yet he admitted that he had discussed this idea "for fun"[47] and, as bishop of Lisieux, he rejected it on the basis of Biblical passages. Oresme's translation-commentary was written in French (which Copernicus did not understand) and was first printed in 1941–1943. Had Copernicus been familiar with it, he would have noticed its complete silence about the earth's orbital revolution. He would surely have been impressed by Oresme's reasoning that the earth benefits from the sun's heat, and in familiar contexts, that what "is roasted at a fire receives the heat of the fire around itself because it is turned and not because the fire is turned around it."[48] That Copernicus had any direct acquaintance with Oresme seems out of the question.

Nevertheless, university teaching may well have been affected by Oresme and even more by his older friend, Jean Buridan. The latter's discussion in Latin of Aristotle's *De caelo* mentioned the idea that "the earth, water, and air in its lower region move jointly with the daily rotation."[49] Buridan also set forth the following argument:

> An arrow shot vertically upward from a bow falls back on the same place on the earth from which it was discharged. This would not happen if the earth moved so fast. In fact, before the arrow fell, the part of the earth from which it was fired would be a mile away.[50]

The absence of the earth's orbital revolution from the thinking of Copernicus' Muslim and Christian predecessors, as well as his use of Arabic observational results, indicate that he did not conceal any intellectual indebtedness to them. On the other hand, with complete openness he expressly acknowledged being inspired by his ancient geodynamic forerunners. Their ideas, however, came down to him as the barest of bones; it was he who first fleshed out the geodynamic astronomy.

Copernicus did away with the stationary earth situated at the center of the Aristotelian-Ptolemaic universe. In his cosmos the earth revolved around the central sun in an annual orbit and at the same time executed its daily rotations. Consequently, the astronomer who inhabits the earth watches the stately celestial ballet from an observatory that is itself both spinning and advancing.

> If any motion is ascribed to the earth, in all things outside it the same motion will appear, but in the opposite direction, as though they were moving past it. This is the nature in particular of the daily rotation, since it seems to involve the entire universe, except the earth and what is around it. However, if you grant that the heavens have no part in this motion but that the earth rotates from west to east, upon earnest consideration you will find that this is the actual situation, as far as concerns the apparent rising and setting of the sun, moon, stars, and planets.[51]

Three of the planets in Copernicus' cosmos revolve around the sun in orbits larger in size and longer in period than the earth's. Each of these three outer, or superior, planets (Mars, Jupiter, and Saturn in ascending order)

> seems from time to time to retrograde, and often to become stationary. This happens by reason of the motion, not of the planet, but of the earth changing its position in the grand circle. For since the earth moves more rapidly than the planet, the line of sight directed [from the earth] toward [the planet and] the firmament regresses, and the earth more than neutralizes the motion of the planet. This regression is most notable when the earth is nearest to the planet, that is, when it comes between the sun and the planet at the evening rising of the planet. On the other hand, when the planet is setting in the evening or rising in the morning, the earth makes the observed motion greater than the actual. But when the line of sight is moving in the direction opposite to that of the planets and at an equal rate, the planets appear to be stationary, since the opposed motions neutralize each other.[52]

As an outer planet in its normal eastward progression (viewed against the background of the more distant stars) slows down, stops, reverses its direction, stops again, and resumes its direct march, it appears to pass through kinks or loops. These were actual celestial happenings for Ptolemy and his followers. The true nature of these planetary loops was revealed for the first time by Copernicus when he analyzed them in detail as side effects of the observation of the slower planet from the faster earth. The loops are optical illusions, not real itineraries.

> Two entirely different motions in longitude appear in them [the planets]. One is caused by the earth's motion . . . and the other is each [planet's] own proper motion. I have decided without any impropriety to call the first one a parallactic motion, since it is this which makes the stations, direct motions, and retrogressions appear in all of them. These phenomena appear, not because the planet, which always moves forward with its own motion, is erratic in this way, but because a sort of parallax is produced by the earth's motion according as it differs in size from those orbits.[53]

Before Copernicus there was much uncertainty regarding the position of Venus and Mercury in the heavens. But the Copernican system located these two bodies correctly as the inferior, or lower, planets, revolving around the central sun inside the earth's orbit and at a greater speed.

> The true places of Saturn, Jupiter, and Mars become visible to us only at their evening rising, which occurs about the middle of their retrogradations. For at that time they coincide with the straight line through the mean place of the sun [and earth], and are unaffected by that parallax. For Venus and Mercury, however, a different relation prevails. For when they are in conjunction with the sun, they are completely blotted out, and are visible only while executing their elongations to either side of the sun, so that they are never found without this parallax.
>
> Consequently each planet has its own individual parallactic revolution, I mean, terrestrial motion in relation to the planet, which these two bodies perform mutually. Combined in this way, the motions of both bodies display themselves interconnected. . . . The motion in parallax, I submit, is nothing but the difference by which the earth's uniform motion exceeds the planets' motion, as in the cases of Saturn, Jupiter, and Mars, or is exceeded by it, as in the cases of Venus and Mercury.[54]

The motion in parallax is smaller, as regards the inner planets, for Venus than for Mercury; and as regards the outer planets, smaller for Mars than for Jupiter and Saturn. Hence,

> the forward and backward arcs appear greater in Jupiter than in Saturn and smaller than in Mars, and on the other hand, greater in Venus than in Mercury. This reversal of direction appears more frequently in Saturn than in Jupiter, and also more rarely in Mars and Venus than in Mercury.[55]

Although the sun was nominally one of the seven Ptolemaic planets, it actually possessed a privileged status in that system. Thus, the center of the epicycle on which Venus was mounted kept exact pace with the sun. This synchronization was accomplished by having the line drawn from the central stationary earth to the annually revolving sun always pass through the center of Venus' epicycle. As a result, Venus' maximum distance to either side of the sun was regulated by the length of the radius of its epicycle. In Ptolemy's words, "the greatest elongations of Venus and Mercury [occur] when the planet reaches the point of contact of the straight line drawn from our eye tangent to the epicycle."[56] This statement applied to Mercury, even though its more irregular motion required a somewhat more complicated arrangement.

In the Ptolemaic theory of the three outer planets the sun again played a special part. As the planet revolved on its epicycle, the radius drawn from the center of the epicycle to the moving planet kept step with the sun revolving around the stationary earth. This coordination was achieved by having the planet's radius vector parallel at all times to the line drawn from the terrestrial observer to the (mean) sun.

Thus, the Ptolemaic theory of each of the three outer and two inner planets introduced the annual revolution. This was imputed by the Ptolemaists to the sun, which they regarded as one of the planets. But they did not explain why the orbital motion of one planet should be so especially privileged as to be an integral part of the theory of five other planets.

In still another respect the sun occupied a privileged position in Ptolemaic astronomy: The sun was placed "between those [planets] which pass through every elongation from it and those which do not so behave, but always move in its vicinity."[57] Copernicus protested that this argument "carried no conviction because its falsity is revealed by the fact that the moon too shows every elongation from the sun."[58] Whatever their other disagreements, Ptolemaists and Copernicans alike separated the moon from the outer planets.

The removal of the sun from the category of the planets was one of Copernicus' most influential contributions to the advancement of astronomy. The limited maximum elongations of Venus and Mercury no longer resulted from the lengths of the radii of their epicycles but were caused by a physical fact: since they were now the inner planets, their orbits lay entirely within the earth's. Therefore, these planets could never be seen from the earth at an angular distance from the sun exceeding 48° for Venus and 28° for Mercury. Hence, these planets could never come to quadrature or opposition, where the difference in geocentric longitude between them and the sun would have to reach 90° or 180°.

In the case of each of the three outer planets, the perpetually parallel orientations of the epicycle's radius directed to the planet and of the line earth-sun were no longer an unexplained coincidence but rather an indication of a physical phenomenon, the earth's orbital revolution around the sun. This "one motion of the earth causes all these phenomena, which the ancient astronomers sought to obtain by means of an epicycle for each" of the three outer planets.[59] By making the earth a planet (or planetizing it, so to say) and deplanetizing the sun, Copernicus took a long step away from previous misconceptions toward the correct understanding of our physical universe:

> Venus seems at times to retrograde, particularly when it is nearest to the earth, like the superior planets, but for the opposite reason. For the regression of the superior planets happens because the motion of the earth is more rapid than theirs, but with Venus, because it is slower; and because the superior planets enclose the grand circle [earth's orbit], whereas Venus is enclosed within it. Hence Venus is never in opposition to the

> sun, since the earth cannot come between them, but it moves within fixed distances on either side of the sun. These distances are determined by tangents to the circumference drawn from the center of the earth, and never exceed 48° in our observations.[60]

From the maximum elongation of Venus, Copernicus was able to obtain the first approximately correct planetary distances, which he expressed in terms of the distance earth-sun. This distance, which subsequently became the fundamental astronomical unit, was grossly underestimated by Copernicus, who simply followed the ancient error in this respect. But in computing the distances of the other five planets from the sun as ratios of the distance earth-sun, Copernicus came remarkably close to the values accepted today. For Mars and Venus, he agreed to the second decimal place (1.52, 0.72), and for Jupiter to the first (5.2). For Saturn and Mercury, however, he was less accurate (9.2 as compared with 9.5; 0.376 as compared with 0.387).

In this respect the contrast with the geocentric astronomy is instructive. Ptolemy was familiar with two proposed locations for Venus and Mercury; either below the sun or above it. No transits of the sun by either Venus or Mercury had ever been observed. But the absence of such reports could be explained if the inferior planet's plane did not coincide with the sun's. "Nor can such a determination be reached in any other way, because none of the planets undergoes a perceptible parallax, the only phenomenon from which the [planetary] distances are obtained."[61] Differences in parallax were regarded by Ptolemy as the only method for arranging the planets in the ascending order of distance from the earth. Such parallaxes being unavailable to him, in the *Syntaxis* he virtually renounced the effort to ascertain the distances of the planets. But Copernicus, by using the astronomical unit as his measuring rod, succeeded in establishing the correct order and distance of the known planets with a high degree of accuracy.

Although he did not accept the widespread belief that every planet was moved by a resident angel or spirit, he prudently refrained from explicitly rejecting that popular doctrine. He held instead that, just as physical bodies become spherical when they are unified, so

> the motion appropriate to a sphere is rotation in a circle. By this very act the sphere expresses its form as the simplest body, wherein neither beginning nor end can be found, nor can the one be distinguished from the other, while the sphere itself traverses the same points to return upon itself.[62]

Had Copernicus possessed the courage or insight to push this principle to its logical outcome, he would not have left the axial rotation of the sun and planets to be discovered by his followers.

The Copernican celestial spheres, which expressed their form by rotating in a circle, were mainly those which carried either the planets or the planet-carrying spheres. In the former case, the planet was attached to the surface of the sphere at its equator, like a pearl on a ring; however, whereas the pearl was visible, the ring was not. Equally invisible was the rest of the planet-carrying sphere, that is, the sphere of the epicycle. The whole of the deferent sphere, which carried the sphere of the epicycle, was likewise imperceptible. Although Copernicus never explicitly asserted the physical existence of these unseen spheres, he never denied their reality and always implicitly assumed it. Thus, *orbium* in the title of his *De revolutionibus orbium coelestium* referred not to the planetary bodies themselves but to the spheres which carried them or helped to do so. In banishing these spheres from astronomy, Tycho Brahe said,

> There really are not any spheres in the heavens. . . . Those which have been devised by the experts to save the appearances exist only in the imagination, for the purpose of enabling the mind to conceive the motion which the heavenly bodies trace in their course and, by the aid of geometry, to determine the motion numerically through the use of arithmetic.[63]

Although Copernicus always proceeded on the assumption that the planetary motions were produced by spheres of one sort or another, he was not unswervingly committed to any particular kind of sphere. Thus, in expounding the motion of the solar apogee, he resorted to an eccentreccentric—that is, an eccentric sphere or circle whose center was carried around by the circumference of a second, smaller eccentric sphere or circle. Then he explained that equivalent results would follow from an epicyclepicyclet—that is, an epicyclet whose center was carried round by an epicycle, whose center in turn revolved on the circumference of a deferent concentric with the sun as the center of the universe. Moreover, mounting an epicycle on an eccentric would serve the purpose as well: "Since so many arrangements lead to the same numerical outcome, I could not readily say which exists, except that on account of the unceasing agreement of the computations and the phenomena I must believe it to be one of them."[64]

In his youthful *Commentariolus* Copernicus located each of the three outer planets on an epicyclet, whose center rode on a larger epicycle carried by a concentric deferent. This device has been called "concentrobiepicyclic" in contradistinction to the eccentrepicyclic arrangement preferred by Copernicus in his mature *De* *revolutionibus.* His later shift to the single epicycle mounted on an eccentric deferent was not arbitrary: it was connected with his conclusion that the sun's displacement from the center of the universe was variable and not constant, as he had originally believed on the strength of Ptolemy's statement to that effect.

The center of Copernicus' universe was not the body of the sun, but a nearby unoccupied point. This purely mathematical entity could not fulfill the function served by the center of the pre-Copernican universe. In that cosmos, according to Aristotle, its principal architect, "the earth and the universe happen to have the same center. A heavy body moves also toward the center of the earth, but it does so only incidentally, because the earth has its center at the center of the universe."[65] Having planetized the earth and raised it out of the universe's center to the third circumsolar orbit, Copernicus could not regard his new planet as the collection depot for all the heavy bodies on the move in the universe. On the other hand, he had no reason to deny that heavy terrestrial objects tended toward the earth's center. Hence, he put forward a revised conception of gravity, according to which heavy objects everywhere tended toward their own center—heavy terrestrial objects toward the center of the earth, heavy lunar objects toward the center of the moon, and so on:

> For my part, I think that gravity is nothing but a certain natural striving with which parts have been endowed . . . so that by assembling in the form of a sphere they may join together in their unity and wholeness. This tendency may be believed to be present also in the sun, the moon, and the other bright planets, so that it makes them keep that roundness which they display.[66]

Whereas the pre-Copernican cosmos had known only a single center of gravity or heaviness, the physical universe acquired multiple centers of gravity from Copernicus, who thus opened the road that led to universal gravitation.

This contribution to one of the basic concepts of modern physics and cosmology confirms what we have already witnessed in many other aspects of Copernicus' thought. He was firmly convinced that he was talking about the actual physical world when he transformed the earth from the sluggish dregs of the universe to a satellite spinning about its axis as it whirled around the sun. He would have spurned the doctrine (had he been familiar with it) propounded by Buridan, who said, "For astronomers, it is enough to assume a way of saving the phenomena, whether it is really so or not."[67]

By a quirk of fate, control over the printing of the first edition of Copernicus' *De revolutionibus* passed into the hands of an editor who shared Buridan's fictionalist conception of scientific method in astronomy. Taking advantage of the dying author's remoteness from the printing shop and at the same time concealing his own identity, Andreas Osiander inserted in the most prominent place available, the verso of the title page, an unsigned address "To the Reader, Concerning the Hypotheses of This Work." Therein the reader was not informed that Copernicus used the word "hypothesis" in its strictly etymological sense as equivalent to "fundamental categorical proposition," not in the derivative meaning of "tentative conjecture." Nor was the reader told that in private correspondence with the editor, Copernicus had steadfastly repudiated the principal tenet in the interpolated address: The astronomer's "hypotheses need not be true nor even probable; if they provide a calculus consistent with the observations, that alone is sufficient."[68] Thus it came to pass that Copernicus' *De revolutionibus,* now universally recognized as a classic of science, was first presented to the civilized world in a guise which, however well intentioned, falsified its essential nature and fooled many readers, including J. B. J. Delambre, the renowned nineteenth-century historian of astronomy.

NOTES

1. Albert Caprinus, *Indicium astrologicum* (Cracow, 1542), dedication (cited in Prowe, I, 1, 148).
2. Rosen, p. 111.
3. Prowe, I, 1, 291.
4. Rosen, p. 67.
5. *De revolutionibus,* IV, 7; cf. III, 18, 19.
6. Simon Starowolski's biography of Copernicus (cited in Prowe, I, 1, 149).
7. Rosen, p. 58.
8. *Ibid.,* p. 59.
9. *Ibid.*
10. *De revolutionibus,* III, 2.
11. *Ibid.,* 13.
12. *Gesamtausgabe,* II, 30.
13. III, 1; Heiberg, ed., I, 203:10, 206:5-6, 25.
14. Plutarch, *Face in the Moon,* 923A.
15. Thomas L. Heath, *Aristarchus of Samos* (Oxford, 1959), p. 302 (trans. modified).
16. Heath, *The Works of Archimedes* (Cambridge, 1897; Dover ed., New York, n.d.), p. 222 (trans. modified).
17. Rosen, p. 58.
18. *De revolutionibus,* I, 6.
19. *Ibid.*
20. *Ibid.,* 8.
21. *Gesamtausgabe,* II, 31.
22. *De revolutionibus,* I, 7.
23. *Ibid.,* 8.
24. *Ibid.*
25. *Ibid.*
26. *Ibid.*
27. *Ibid.*
28. *Ibid.,* 7.

29. *Ibid.*, 8.
30. *Ibid.*, 7.
31. *Ibid.*, 8.
32. *Ibid.*, 7.
33. Rosen, p. 63.
34. *Ibid.*, pp. 63–64.
35. *De revolutionibus*, I, 11.
36. *Ibid.*
37. *Ibid.*, III, 1.
38. *Ibid.*, 16.
39. *Ibid.*, 20.
40. *Ibid.*, 16.
41. *Ibid.*, 20.
42. Rosen, p. 125.
43. *De revolutionibus*, IV, 27.
44. Rosen, p. 72.
45. *De revolutionibus*, IV, 2.
46. Rosen, pp. 57–58.
47. Nicole Oresme, "Le livre du ciel et du monde," ed. and with commentary by Albert D. Menut and Alexander J. Denomy, in *Mediaeval Studies*, **4** (1942), 279 (§144c).
48. *Ibid.*, p. 277 (§142b).
49. *Questiones super libris quattuor De caelo et mundo*, E. A. Moody, ed. (Cambridge, Mass., 1942), p. 229.
50. *Ibid.*
51. *De revolutionibus*, I, 5.
52. Rosen, pp. 77–78.
53. *De revolutionibus*, V, 1.
54. *Ibid.*
55. *Ibid.*, I, 10.
56. Ptolemy, *Syntaxis mathematica*, X, 6; Heiberg, ed., II, 317:13–17.
57. *Ibid.*, IX, 1; Heiberg, ed., II, 207:18–20.
58. *De revolutionibus*, I, 10.
59. *Ibid.*, V, 3.
60. Rosen, p. 83.
61. Ptolemy, IX, 1; Heiberg, ed., II, 207:13–16.
62. *De revolutionibus*, I, 4.
63. Tycho Brahe, *Opera omnia*, J. L. E. Dreyer, ed., 15 vols. (Copenhagen, 1913–1929), IV, 222:24–28.
64. *De revolutionibus*, III, 20.
65. Aristotle, *De caelo*, II, 14; 296b15–18.
66. *De revolutionibus*, I, 9.
67. Buridan, p. 229.
68. Rosen, p. 25.

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A 2nd ed. of Henryk Baranowski's *Bibliografia kopernikowska 1509–1955* (Warsaw, 1958) is being prepared in connection with the celebration in 1973 of the 500th anniversary of the birth of Copernicus. An annotated Copernicus bibliography for 1939–1958 is included in *Three Copernican Treatises*, trans., ed., and with an introduction by Edward Rosen, 2nd ed. (New York, 1959), which also contains an English translation of Copernicus' *Commentariolus* and *Letter Against Werner* and Rheticus' *Narratio prima*. An English translation of Copernicus' *De revolutionibus orbium coelestium* is in Great Books of the Western World, vol. XVI (Chicago, 1952). The Latin text of *De revolutionibus* and a photocopy of Copernicus' autograph manuscript are available in *Nikolaus Kopernikus Gesamtausgabe*, 2 vols. (Berlin–Munich, 1944–1949). The standard biography by Leopold Prowe, *Nicolaus Coppernicus*, 2 vols. (Berlin, 1883–1884; repr., Osnabrück, Germany, 1967), has not yet been superseded, even though it is incomplete (the planned third volume was never published), nationalistically biased, scientifically inadequate, somewhat inaccurate, and partly obsolete.

EDWARD ROSEN

CORDIER, PIERRE-LOUIS-ANTOINE (*b.* Abbeville, France, 31 March 1777; *d.* Paris, France, 30 March 1861), *geology, mineralogy.*

Cordier was a pioneer in the geological, technical, and economic analysis of French mines, particularly coal mines. He began the use of the polarizing microscope in the study of the constituents of rocks. As a counsellor of state and later a peer during the reign of Louis Philippe, he played an important role in the organization of French railroads, steamboat navigation, and road construction. For three decades he was president of the Conseil des Mines, which afforded him a powerful voice in French mining affairs.

After completing his early education at Abbeville, Cordier went to Paris in 1794 and entered the École des Mines in 1795. He was named engineer in 1797, and in 1798 he was selected by Dolomieu to accompany him to Egypt as a member of the scientific commission of the French expedition. Cordier was an English prisoner for a short time when the venture failed, and returned to France in 1799. He traveled through Belgium, Switzerland, Italy, and Spain until 1803, when he was assigned as engineer in the Department of the Apennines. He became divisional inspector of mines in 1810.

Two of Cordier's early mineral surveys were "Statistique du département du Lot" and "Statistique minéralogique du département des Apennins." These were detailed analyses of the terrain, geology, mineral deposits, and mining and metallurgical works of the two departments. In 1815 Cordier published the memoir "Description technique et économique des mines de houille de Saint-Georges-Chatelaison." This important coal mining property had become the subject of litigation; and Cordier had been appointed as an expert to evaluate the condition of the mines for the court, so that it could judge the rights and interests of the parties involved. The editors of the *Journal des mines* termed Cordier's work one of the most difficult and delicate missions with which an engineer of mines could be charged.

Also in 1815 Cordier published a complete survey of French coal mines and coal production, "Sur les mines de houille de France et l'importation des houilles étrangères." He reported that coal consumption in France had doubled during the period 1789–1812, owing mainly to the substitution of coal for wood, and that French coal production had tripled in the same period because of the cessation of English