entirely appropriate to his seminal role in the development of astronomy. Copernicus was a dedicated specialist. He belonged to the revived Hellenistic tradition of mathematical astronomy which emphasized the mathematical problem of the planets at the expense of cosmology. For his Hellenistic predecessors the physical incongruity of an epicycle had not been an important drawback of the Ptolemaic system, and Copernicus displayed a similar indifference to cosmological detail when he failed to note the incongruities of a moving earth in an otherwise traditional universe. For him, mathematical and celestial detail came first; he wore blinders that kept his gaze focused upon the mathematical harmonies of the heavens. To anyone who did not share his specialty Copernicus' view of the universe was narrow and his sense of values distorted.

But an excessive concern with the heavens and a distorted sense of values may be essential characteristics of the man who inaugurated the revolution in astronomy and cosmology. The blinders that restricted Copernicus' gaze to the heavens may have been functional. They made him so perturbed by discrepancies of a few degrees in astronomical prediction that in an attempt to resolve them he could embrace a cosmological heresy, the earth's motion. They gave him an eye so absorbed with geometrical harmony that he could adhere to his heresy for its harmony alone, even when it had failed to solve the problem that had led him to it. And they helped him evade the nonastronomical consequences of his innovation, consequences that led men of less restricted vision to reject his innovation as absurd.

Above all, Copernicus' dedication to the celestial motions is responsible for the painstaking detail with which he explored the mathematical consequences of the earth's motion and fitted those consequences to an existing knowledge of the heavens. That detailed technical study is Copernicus' real contribution. Both before and after Copernicus there were cosmologists more radical than he, men who with broad brush strokes sketched an infinite and multipopulated universe. But none of them produced work resembling the later books of the *De Revolutionibus*, and it is these books which, by showing for the first time that the astronomer's job could be done, and done more harmoniously, from a moving earth, provided a stable base from which to launch a new astronomical tradition. Had Copernicus' cosmological First Book appeared alone, the Copernican Revolution would and should be known by someone else's name.

6

THE ASSIMILATION OF COPERNICAN ASTRONOMY

The Reception of Copernicus' Work

Copernicus died in 1543, the year in which the *De Revolutionibus* was published, and tradition tells us that he received the first printed copy of his life's work on his deathbed. The book had to fight its battles without further help from its author. But for those battles Copernicus had constructed an almost ideal weapon. He had made the book unreadable to all but the erudite astronomers of his day. Outside of the astronomical world the *De Revolutionibus* created initially very little stir. By the time large-scale lay and clerical opposition developed, most of the best European astronomers, to whom the book was directed, had found one or another of Copernicus' mathematical techniques indispensable. It was then impossible to suppress the work completely, particularly because it was in a printed book and not, like Oresme's work or Buridan's, in a manuscript. Whether intentionally or not, the final victory of the *De Revolutionibus* was achieved by infiltration.

For two decades before the publication of his principal work Copernicus had been widely recognized as one of Europe's leading astronomers. Reports about his research, including his new hypothesis, had circulated since about 1515. The publication of the *De Revolutionibus* was eagerly awaited. When it appeared, Copernicus' contemporaries may have been skeptical of its main hypothesis and disappointed in the complexity of its astronomical theory, but they were nevertheless forced to recognize Copernicus' book as the first European astronomical text that could rival the *Almagest* in depth and completeness. Many advanced astronomical texts written during the fifty years after Copernicus' death referred to him as a "second

Ptolemy" or "the outstanding artificer of our age"; increasingly these books borrowed data, computations, and diagrams from the *De Revolutionibus*, at least from parts of it independent of the motion of the earth. During the second half of the sixteenth century the book became a standard reference for all those concerned with advanced problems of astronomical research.

But the success of the *De Revolutionibus* does not imply the success of its central thesis. The faith of most astronomers in the earth's stability was at first unshaken. Authors who applauded Copernicus' erudition, borrowed his diagrams, or quoted his determination of the distance from the earth to the moon, usually either ignored the earth's motion or dismissed it as absurd. Even the rare text that mentioned Copernicus' hypothesis with respect rarely defended or used it. With a few notable exceptions, the most favorable of the early reactions to the Copernican innovation are typified by the remark of the English astronomer Thomas Blundeville, who wrote: "Copernicus . . . affirmeth that the earth turneth about and that the sun standeth still in the midst of the heavens, by help of which false supposition he hath made truer demonstrations of the motions and revolutions of the celestial spheres, than ever were made before."[1] Blundeville's remark appeared in 1594 in an elementary book on astronomy that took the earth's stability for granted. Yet the tenor of Blundeville's rejection must have sent his more alert and proficient readers straight to the *De Revolutionibus*, a book which, in any case, no proficient astronomer could ignore. From the start the *De Revolutionibus* was widely read, but it was read in spite of, rather than because of, its strange cosmological hypothesis.

Nevertheless, the book's large audience ensured it a small but increasing number of readers equipped to discover Copernicus' harmonies and willing to admit them as evidence. There were a few converts, and their work helped in varied ways to spread knowledge of Copernicus' system. The *Narratio Prima* or *First Account* by Copernicus' earliest disciple, George Joachim Rheticus (1514–1576), remained the best brief technical description of the new astronomical methods for many years after its first publication in 1540. The popular elementary defense of Copernicanism published in 1576 by the English astronomer Thomas Digges (*c.*1546–1595) did much to spread the concept of the earth's motion beyond the narrow circle of astronomers. And the teaching and research of Michael Maestlin (1550–1631), professor of astronomy at the University of Tübingen, gained a few converts, including Kepler, for the new astronomy. Through the teaching, writing, and research of men like these, Copernicanism inevitably gained ground, though the astronomers who avowed their adherence to the conception of a moving earth remained a small minority.

But the size of the group of avowed Copernicans is not an adequate index of the success of Copernicus' innovation. Many astronomers found it possible to exploit Copernicus' mathematical system and to contribute to the success of the new astronomy while denying or remaining silent about the motion of the earth. Hellenistic astronomy provided their precedent. Ptolemy himself had never pretended that all of the circles used in the *Almagest* to compute planetary position were physically real; they were useful mathematical devices and they did not have to be any more than that. Similarly, Renaissance astronomers were at liberty to treat the circle representing the earth's orbit as a mathematical fiction, useful for computations alone; they could and occasionally did compute planetary position *as if* the earth moved without committing themselves to the physical reality of that motion. Andreas Osiander, the Lutheran theologian who saw Copernicus' manuscript through the press, had actually urged this alternative upon readers in an anonymous preface attached to the *De Revolutionibus* without Copernicus' permission. The spurious preface probably did not fool many astronomers, but a number of them nevertheless took advantage of the alternative that it suggested. Using Copernicus' mathematical system without advocating the physical motion of the earth provided a convenient escape from the dilemma posed by the contrasting celestial harmonies and terrestrial discord of the *De Revolutionibus*. It also gradually tempered the astronomer's initial conviction that the earth's motion was absurd.

Erasmus Reinhold (1511–1553) was the first astronomer to do important service for the Copernicans without declaring himself in favor of the earth's motion. In 1551, only eight years after the publication of the *De Revolutionibus*, he issued a complete new set of astronomical tables, computed by the mathematical methods developed by Copernicus, and these soon became indispensable to astronomers and astrologers, whatever their beliefs about the position and motion of the earth. Reinhold's *Prutenic Tables*, named for his patron, the

Duke of Prussia, were the first complete tables prepared in Europe for three centuries, and the old tables, which had included some errors from the start, were now badly out of date – the clock had run too long. Reinhold's supremely careful work, based on somewhat more and better data than had been available to the men who computed the thirteenth-century tables, produced a set of tables which, for most applications, were measurably superior to the old. They were not, of course, completely accurate; Copernicus' mathematical system was intrinsically no more accurate than Ptolemy's; errors of a day in the prediction of lunar eclipses were common, and the length of the year determined from the *Prutenic Tables* was actually slightly less accurate than that determined from the older tables. But most comparisons displayed the superiority of Reinhold's work, and his tables became increasingly an astronomical requisite. Since the tables were known to derive from the astronomical theory of the *De Revolutionibus*, Copernicus' prestige inevitably gained. Every man who used the *Prutenic Tables* was at least acquiescing in an implicit Copernicanism.

During the second half of the sixteenth century astronomers could dispense with neither the *De Revolutionibus* nor the tables based upon it. Copernicus' proposal gained ground slowly but apparently inexorably. Successive generations of astronomers, decreasingly predisposed by experience and training to take the earth's stability for granted, found the new harmonies a more and more forceful argument for its motion. Besides, by the end of the century the first converts had begun to uncover new evidence. Therefore if the decision between the Copernican and the traditional universe had concerned only astronomers, Copernicus' proposal would almost certainly have achieved a quiet and gradual victory. But the decision was not exclusively, or even primarily, a matter for astronomers, and as the debate spread from astronomical circles it became tumultuous in the extreme. To most of those who were not concerned with the detailed study of celestial motions, Copernicus' innovation seemed absurd and impious. Even when understood, the vaunted harmonies seemed no evidence at all. The resulting clamor was widespread, vocal, and bitter.

But the clamor was slow in starting. Initially, few nonastronomers knew of Copernicus' innovation or recognized it as more than a passing individual aberration like many that had come and gone before. Most of the elementary astronomy texts and manuals used during the second half of the sixteenth century had been prepared long before Copernicus' lifetime – John of Holywood's thirteenth-century primer was still a leader in elementary training – and the new handbooks prepared after the publication of the *De Revolutionibus* usually did not mention Copernicus or dismissed his innovation in a sentence or two. The popular cosmological books that described the universe to laymen remained even more exclusively Aristotelian in tone and substance; Copernicus was either unknown to their authors or, if known, he was usually ignored. Except, perhaps, in a few centers of Protestant learning, Copernicanism does not seem to have been a cosmological issue during the first few decades after Copernicus' death. Outside of astronomical circles it seldom became a major issue until the beginning of the seventeenth century.

There were a few sixteenth-century reactions from nonastronomers, and they provide a foretaste of the immense debate to follow, for they were usually unequivocally negative. Copernicus and his few followers were ridiculed for the absurdity of their concept of a moving earth, though without the bitterness or the elaborate dialectic which developed when it became apparent that Copernicanism was to be a stubborn and dangerous opponent. One long cosmological poem, first published in France in 1578 and immensely popular there and in England during the next century and a quarter, provides the following typical description of the Copernicans as

> Those clerks who think (think how absurd a jest)
> That neither heav'ns nor stars do turn at all,
> Nor dance about this great round earthly ball;
> But th'earth itself, this massy globe of ours,
> Turns round-about once every twice-twelve hours:
> And we resemble land-bred novices
> New brought aboard to venture on the seas;
> Who, at first launching from the shore, suppose
> The ship stands still, and that the ground it goes. . . .
> So, never should an arrow, shot upright,
> In the same place upon the shooter light;
> But would do, rather, as, at sea, a stone
> Aboard a ship upward uprightly thrown;
> Which not within-board falls, but in the flood
> Astern the ship, if so the wind be good.
> So should the fowls that take their nimble flight
> From western marches towards morning's light; . . .

And bullets thundered from the cannon's throat
(Whose roaring drowns the heav'nly thunder's note)
Should seem recoil: since the quick career,
That our round earth should daily gallop here,
Must needs exceed a hundred-fold, for swift,
Birds, bullets, winds; their wings, their force, their drift.
Arm'd with these reasons, 'twere superfluous
T'assail the reasons of Copernicus;
Who, to save better of the stars th'appearance,
Unto the earth a three-fold motion warrants.[2]

Since the author of this poetic rejection of Copernicanism was a poet, not a scientist or philosopher, his cosmological conservatism and his adherence to classic sources may not be surprising. Yet it was from poets and popularizers rather than from astronomers that most people in the sixteenth and seventeenth century, as today, learned about the universe. Du Bartas's *The Week, or the Creation of the World*, from which the preceding excerpt is taken, was a far more widely read and influential book than the *De Revolutionibus*.

In any case, uncritical offhand condemnations of Copernicus and his followers were not restricted to conservative and unoriginal popularizers. Jean Bodin, famous as one of the most advanced and creative political philosophers of the sixteenth century, discards Copernicus' innovation in almost identical terms:

> No one in his senses, or imbued with the slightest knowledge of physics, will ever think that the earth, heavy and unwieldy from its own weight and mass, staggers up and down around its own center and that of the sun; for at the slightest jar of the earth, we would see cities and fortresses, towns and mountains thrown down. A certain courtier Aulicus, when some astrologer in court was upholding Copernicus' idea before Duke Albert of Prussia, turning to the servant who was pouring the Falernian, said: "Take care that the flagon is not spilled." For if the earth were to be moved, neither an arrow shot straight up, nor a stone dropped from the top of a tower would fall perpendicularly, but either ahead or behind. . . . Lastly, all things on finding places suitable to their natures, remain there, as Aristotle writes. Since therefore the earth has been allotted a place fitting its nature, it cannot be whirled around by other motion than its own.[3]

In this passage Bodin looks a traditionalist, but he was not. Because of its generally radical and atheistic tone, the book from which the quotation is taken was in 1628 placed upon the Index of books that Catholics are forbidden to read. Although its author was himself a Catholic, the book remains there to this day. Bodin was quite willing to break with tradition, but that was not enough to make a man a Copernican. It was almost invariably also necessary to understand astronomy and to take its problems immensely seriously. Except to those with an astronomical bias, the earth's motion seemed very nearly as absurd in the years after Copernicus' death as it had before.

The anti-Copernican arguments suggested by Du Bartas and Bodin can be considerably elaborated along lines anticipated by our discussions of the Aristotelian universe in Chapters 3 and 4. In one or another disguise, which we need not penetrate, they appear again and again during the first half of the seventeenth century when the debate about the earth's motion became bitter and intense. The earth's motion, it was said, violates the first dictate of common sense; it conflicts with long-established laws of motion; it has been suggested merely "to save better of the stars th'appearance," a ridiculously minuscule incentive for revolution. These are forceful arguments, quite sufficient to convince most people. But they are not the most forceful weapons in the anti-Copernican battery, and they are not the ones that generated the most heat. Those weapons were religious and, particularly, scriptural.

Citation of Scripture against Copernicus began even before the publication of the *De Revolutionibus*. In one of his "Table Talks," held in 1539, Martin Luther is quoted as saying:

> People gave ear to an upstart astrologer who strove to show that the earth revolves, not the heavens or the firmament, the sun and the moon. . . . This fool wishes to reverse the entire science of astronomy; but sacred Scripture tells us [Joshua 10:13] that Joshua commanded the sun to stand still, and not the earth.[4]

Luther's principal lieutenant, Melanchthon, soon joined in the increasing Protestant clamor against Copernicus. Six years after Copernicus' death he wrote:

> The eyes are witnesses that the heavens revolve in the space of twenty-four hours. But certain men, either from the love of novelty, or to make a display of ingenuity, have concluded that the earth moves; and they maintain that neither the eighth sphere nor the sun revolves. . . . Now, it is a want of honesty and decency to assert such notions publicly, and the example is pernicious. It is the part of a good mind to accept the truth as revealed by God and to acquiesce in it.[5]

Melanchthon then proceeded to assemble a number of anti-Copernican Biblical passages, emphasizing the famous verses, Ecclesiastes 1:4–5, which state "the earth abideth forever" and that "The sun also ariseth, and the sun goeth down, and hasteth to his place where he arose." Finally he suggests that severe measures be taken to restrain the impiety of the Copernicans.

Other Protestant leaders soon joined in the rejection of Copernicus. Calvin, in his *Commentary on Genesis*, cited the opening verse of the Ninety-third Psalm — "the earth also is stablished, that it cannot be moved" — and he demanded, "Who will venture to place the authority of Copernicus above that of the Holy Spirit?"[6] Increasingly, Biblical citation became a favored source of anti-Copernican argument. By the first decades of the seventeenth century clergymen of many persuasions were to be found searching the Bible line by line for a new passage that would confound the adherents of the earth's motion. With growing frequency Copernicans were labeled "infidel" and "atheist," and when, after about 1610, the Catholic Church officially joined the battle against Copernicanism, the charge became formal heresy. In 1616 the *De Revolutionibus* and all other writings that affirmed the earth's motion were put upon the Index. Catholics were forbidden to teach or even to read Copernican doctrines, except in versions emended to omit all reference to the moving earth and central sun.

The preceding sketch displays the most popular and forceful weapons in the arsenal arrayed against Copernicus and his followers, but it scarcely indicates what the war was really about. Most of the men quoted above are so ready to reject the earth's motion as absurd or as conflicting with authority that they fail to show, and may not at first have realized fully, that Copernicanism was potentially destructive of an entire fabric of thought. Their very dogmatism disguises their motives. But it does not eliminate them. More than a picture of the universe and more than a few lines of Scripture were at stake. The drama of Christian life and the morality that had been made dependent upon it would not readily adapt to a universe in which the earth was just one of a number of planets. Cosmology, morality, and theology had long been interwoven in the traditional fabric of Christian thought described by Dante at the beginning of the fourteenth century. The vigor and venom displayed at the height of the Copernican controversy, three centuries later, testifies to the strength and vitality of the tradition.

When it was taken seriously, Copernicus' proposal raised many gigantic problems for the believing Christian. If, for example, the earth were merely one of six planets, how were the stories of the Fall and of the Salvation, with their immense bearing on Christian life, to be preserved? If there were other bodies essentially like the earth, God's goodness would surely necessitate that they, too, be inhabited. But if there were men on other planets, how could they be descendants of Adam and Eve, and how could they have inherited the original sin, which explains man's otherwise incomprehensible travail on an earth made for him by a good and omnipotent deity? Again, how could men on other planets know of the Saviour who opened to them the possibility of eternal life? Or, if the earth is a planet and therefore a celestial body located away from the center of the universe, what becomes of man's intermediate but focal position between the devils and the angels? If the earth, as a planet, participates in the nature of celestial bodies, it can not be a sink of iniquity from which man will long to escape to the divine purity of the heavens. Nor can the heavens be a suitable abode for God if they participate in the evils and imperfection so clearly visible on a planetary earth. Worst of all, if the universe is infinite, as many of the later Copernicans thought, where can God's Throne be located? In an infinite universe, how is man to find God or God man?

These questions have answers. But the answers were not easily achieved; they were not inconsequential; and they helped to alter the religious experience of the common man. Copernicanism required a transformation in man's view of his relation to God and of the bases of his morality. Such a transformation could not be worked out overnight, and it was scarcely even begun while the evidence for Copernicanism remained as indecisive as it had been in the *De Revolutionibus*. Until that transformation was achieved, sensitive observers might well find traditional values incompatible with the new cosmology, and the frequency with which the charge of atheism was hurled at the Copernicans is evidence of the threat to the established order posed to many observers by the concept of a planetary earth.

But the charge of atheism is only indirect evidence. More forceful testimony comes from men who felt compelled to take the Copernican innovation seriously. As early as 1611, the English poet and divine John Donne said to the Copernicans that "those opinions of yours may very well be true. . . . [In any case, they are now] creeping into every man's mind," [7] but he could discover little except evil in the impending transition. During the same year in which he reluctantly conceded the probability of the earth's motion, he portrayed his discomfort at the impending dissolution of traditional cosmology in *The Anatomy of the World*, a poem in which "the frailty and decay of this whole world is represented." Part of Donne's malaise derived specifically from Copernicanism:

> [The] new Philosophy calls all in doubt,
> The Element of fire is quite put out;
> The Sun is lost, and th'earth, and no man's wit
> Can well direct him where to look for it.
> And freely men confess that this world's spent,
> When in the Planets, and the Firmament
> They seek so many new; then see that this
> Is crumbled out again to his Atomies.
> 'Tis all in pieces, all coherence gone;
> All just supply, and all Relation:
> Prince, Subject, Father, Son, are things forgot,
> For every man alone thinks he hath got
> To be a Phoenix, and that then can be
> None of that kind, of which he is, but he.[8]

Fifty-six years later, when scientists, at least, had overwhelmingly accepted the earth's motion and its status as a planet, Copernicanism presented the same problem of Christian morality to the English poet John Milton, though he resolved it differently. Milton, like Donne, thought that Copernicus' innovation might very well be true. He included in *Paradise Lost* a lengthy description of the two opposing systems of the world, the Ptolemaic and the Copernican, and he refused to take sides in what he described as the abstruse technical controversy between them. But in his epic, whose object was "to justify the ways of God to man," [9] he was compelled to use a traditional cosmological frame. The universe of *Paradise Lost* is not quite Dante's universe; Milton derives the positions of heaven and hell from a tradition even older than Dante's. But the terrestrial stage upon which Milton portrays man's fall is still necessarily a unique, stable, and centrally located body, created by God for man. Though more than a century had passed since the publication of the *De Revolutionibus*, the Christian drama and the morality that had been made dependent upon it could not be adapted to a universe in which the earth was a planet and in which new worlds could continually be discovered "in the Planets and the Firmament."

Donne's uneasiness and Milton's cosmological choice illustrate the extrascientific issues which, during the seventeenth century, were integral parts of the controversy over Copernicanism. These issues, even more than its apparent absurdity or its conflict with established laws of motion, account for the hostility that Copernicus' proposal encountered outside of scientific circles. But they may not quite account either for the intensity of that hostility or for the willingness of both Protestant and Catholic leaders to make anti-Copernicanism an official Church doctrine which could justify the persecution of Copernicans. It is easy to understand the existence of strong resistance to Copernicus' innovation – its patent absurdity and destructiveness were not offset by effective evidence – but it is difficult to understand the extreme forms which that resistance occasionally took. Before the middle of the sixteenth century the history of Christianity offers few precedents for the rigidity with which the official leaders of major religious groups applied the literal text of Scripture to suppress a scientific and cosmological theory. Even during the early centuries of the Catholic Church, when distinguished Church Fathers like Lactantius had employed the Scriptures to destroy classical cosmology, there had been no official Catholic cosmological position to which communicants were required to adhere.

The bitterness of official Protestant opposition is, in practice, far easier to understand than its Catholic counterpart, because the Protestants' opposition can be plausibly related to a more fundamental controversy which arose in the split between the Churches. Luther and Calvin and their followers wished to return to a pristine Christianity, as it could be discovered in the words of Jesus and the early Fathers of the Church. To Protestant leaders the Bible was the single fundamental source of Christian knowledge. They vehemently rejected the ritual and the dialectic subtleties that successive authoritarian Church Councils had interposed between the believer and the fountainhead of his belief. They abhorred the elaborate metaphorical and allegorical interpretation of Scripture, and their literal adherence to the Bible in matters of cosmology had no parallel since the days of Lactantius, Basil, and Kosmas. To them Copernicus may well have seemed a symbol of all the tortuous reinterpretations which, during the later Middle Ages, had separated Christians from the basis of their belief. Therefore the violence of the thunder that official Protestantism directed at Copernicus seems almost natural. Toleration of Copernicanism would have been toleration of the very attitude toward Holy Writ and toward knowledge in general which, according to Protestants, had led Christianity astray.

Copernicanism was thus indirectly involved in the larger religious battle between the Protestant and Catholic Churches, and that involvement must account for some of the excessive bitterness the Copernican controversy evoked. Protestant leaders like Luther, Calvin, and Melanchthon led in citing Scripture against Copernicus and in urging the repression of Copernicans. Since the Protestants never possessed the police apparatus available to the Catholic Church, their repressive measures were seldom so effective as those taken later by the Catholics, and they were more readily abandoned when the evidence for Copernicanism became overwhelming. But Protestants nevertheless provided the first effective institutionalized opposition. Reinhold's silence about the physical validity of the mathematical system that he had employed in computing the *Prutenic Tables* is usually interpreted as an index of the official opposition to Copernicanism at the Protestant university of Wittenberg. Osiander, who added the spurious apologia to the beginning of the *De Revolutionibus*, was also a Protestant. Rheticus, the first outspoken defender of Copernicus' astronomy, was a Protestant, too, but his *Narratio Prima* was written while he was away from Wittenberg and before the *De Revolutionibus* appeared; after his return to Wittenberg he published no more Copernican tracts.

For sixty years after Copernicus' death there was little Catholic counterpart for the Protestant opposition to Copernicanism. Individual Catholic clergymen expressed their incredulity or abhorrence of the new conception of the earth, but the Church itself was silent. The *De Revolutionibus* was read and at least occasionally taught at leading Catholic universities. Reinhold's *Prutenic Tables*, based on Copernicus' mathematical system, were used in the reformation of the calendar promulgated for the Catholic world in 1582 by Gregory

XIII. Copernicus himself had been a cleric and a reputable one, whose judgment was widely sought on astronomical and other matters. His book was dedicated to the Pope, and among the friends who urged him to publish it were a Catholic bishop and a cardinal. During the fourteenth, fifteenth, and sixteenth centuries the Church had not imposed cosmological conformity on its members. The *De Revolutionibus* was itself a product of the latitude allowed to Churchmen in matters of science and secular philosophy, and before the *De Revolutionibus* the Church had spawned even more revolutionary cosmological concepts without theological convulsions. In the fifteenth century the eminent cardinal and papal legate Nicholas of Cusa had propounded a radical Neoplatonic cosmology and had not even bothered about the conflict between his views and Scripture. Though he portrayed the earth as a moving star, like the sun and the other stars, and though his works were widely read and had great influence, he was not condemned or even criticized by his Church.

Therefore, when in 1616, and more explicitly in 1633, the Church prohibited teaching or believing that the sun was at the center of the universe and that the earth moved around it, the Church was reversing a position that had been implicit in Catholic practice for centuries. The reversal shocked a number of devout Catholics, because it committed the Church to opposing a physical doctrine for which new evidence was being discovered almost daily, and because there clearly had been an alternative attitude open to the Church. The same devices which, in the twelfth and thirteenth centuries, had permitted the Church to embrace Ptolemy and Aristotle might, in the seventeenth century, have been applied to Copernicus' proposal. In a limited fashion they had already been applied. Oresme's fourteenth-century discussion of the earth's diurnal rotation had not ignored the scriptural evidence for the earth's immobility. He had cited two of the Biblical passages noted above and had then replied:

> To the . . . argument concerning the Holy Scripture which says that the sun revolves, etc., one would say that it is here conforming to the manner of common human speech, just as is done in several [other] places, e.g., where it is written that God is repentant and that he is angry and pacified and all other things which are not just as they sound. Also appropriate to our question, we read that God covers the heaven with clouds: . . . and yet in reality the heaven covers the clouds.[10]

Though the reinterpretation demanded by Copernicanism would have been more drastic and more costly, the same sort of arguments would have sufficed. During the eighteenth and nineteenth centuries similar arguments were employed, and even in the seventeenth century, at the time when the official decision to prohibit Copernicanism was being taken, a few Catholic leaders recognized that some such far-reaching reformulation might conceivably be required. In 1615 Cardinal Bellarmine, the leader of the Church officials who one year later condemned Copernican views, wrote to the Copernican Foscarini:

> If there were a real proof that the sun is in the center of the universe, that the earth is in the third heaven, and that the sun does not go round the earth but the earth round the sun, then we should have to proceed with great circumspection in explaining passages of Scripture which appear to teach the contrary, and rather admit that we did not understand them than declare an opinion to be false which is proved to be true.[11]

Very probably Bellarmine's liberalism is more apparent than real. The next sentence of his letter reads, "But as for myself, I shall not believe that there are such proofs until they are shown to me," and that sentence was written in full knowledge of the telescopic discoveries by which Galileo had provided strong new evidence for Copernicus' innovation. We may wonder what sort of evidence Bellarmine would have considered "real proof" against the literal word of Scripture. But he was aware, at least in principle, of the possibility of evidence that would necessitate reinterpretation. Only, by the second decade of the seventeenth century, Catholic authorities were giving greater weight to scriptural evidence and allowing less latitude for speculative dissent than they had done for centuries.

Much of the increasingly fundamentalist position that underlies the Catholic condemnation of Copernicus must, I think, be a reaction to the pressures brought to bear upon the Church by the Protestant revolt. Copernican doctrines were, in fact, condemned during the Counter Reformation, just when the Church was most convulsed by internal reforms designed to meet Protestant criticism. Anti-Copernicanism seems, at least in part, one of those reforms. Another cause of the Church's increased sensitivity to Copernicanism after 1610 may well have been a delayed awakening to the fuller theological implications of the earth's motions. In the sixteenth century those implications

had rarely been made explicit. But in 1600 they were emphasized with a clamor heard throughout Europe by the execution of Giordano Bruno, the philosopher and mystic, at the stake in Rome. Bruno was not executed for Copernicanism, but for a series of theological heresies centering in his view of the Trinity, heresies for which Catholics had been executed before. He is not, as he has often been called, a martyr of science. But Bruno had found Copernicus' proposal congenial to his Neoplatonic and Democritean vision of an infinite universe containing an infinity of worlds generated by a fecund deity. He had propounded Copernicanism in England and on the Continent and had given it a significance not to be found in the *De Revolutionibus* (see Chapter 7 below). Certainly the Church feared Bruno's Copernicanism, and that fear may also have stimulated their reaction.

But whatever the reasons, the Church did, in 1616, make Copernicanism a doctrinal issue, and all the worst excesses of the battle against the earth's motion – the condemnation of Copernican opinions, the recantation and "imprisonment" of Galileo, and the dismissal and banishment of prominent Catholic Copernicans – occurred in or after that year. Once the apparatus of the Inquisition had been unleashed upon Copernicanism it was difficult to recall. Not until 1822 did the Church permit the printing of books that treated the earth's motion as physically real, and by then all but the most rigidly orthodox Protestant sects had long been persuaded. The Church's official commitment to the earth's stability did irrevocable harm both to Catholic science and, later, to Church prestige. No episode in Catholic literature has so often or so appropriately been cited against the Church as the pathetic recantation forced upon the aged Galileo in 1633.

Galileo's recantation marks the peak of the battle against Copernicanism, and, ironically, it was not delivered until a time when the outcome of the battle could be foreseen. Before 1610, when the opposition to Copernicus' doctrine was mustering, all but the most fanatical advocates of the earth's motion would have been forced to admit that the evidence for Copernicanism was weak and the counterevidence strong. Perhaps the fundamental premise of the *De Revolutionibus* would have to be abandoned. But by 1633 that was not the case. During the first decades of the seventeenth century new and stronger evidence was discovered, and the complexion of the battle changed. Even before Galileo's recantation, the new evidence had transformed the opposition to Copernicanism into a hopeless rear-guard action. The rest of this chapter examines that new evidence drawn from the heavens by three of Copernicus' immediate successors.

Tycho Brahe

If Copernicus was the greatest European astronomer in the first half of the sixteenth century, Tycho Brahe (1546–1601) was the preëminent astronomical authority of the second. And, judged purely by technical proficiency, Brahe was the greater man. But comparison is largely meaningless, because the two have different strengths and weaknesses which would not readily have merged in a single personality, and both sorts of strength were essential to the Copernican Revolution. As a cosmological and astronomical theorist, Brahe displayed a relatively traditional frame of mind. His work shows little of that Neoplatonic concern with mathematical harmonies that had been instrumental in Copernicus' break with the Ptolemaic tradition and that at the start provided the only real evidence of the earth's motion. He propounded no enduring innovations in astronomical theory. He was, in fact, a lifelong opponent of Copernicanism, and his immense prestige helped to postpone the conversion of astronomers to the new theory.

But though Brahe was no innovator of astronomical concepts, he was responsible for immense changes in the techniques of astronomical observation and in the standards of accuracy demanded from astronomical data. He was the greatest of all naked-eye observers. He designed and built many new instruments, larger, stabler, and better calibrated than those in use before. With great ingenuity he investigated and corrected many errors that developed in using these instruments, establishing a whole series of new techniques for the collection of accurate information about the position of planets and stars. Most important of all, he began the practice of making regular observations of planets as they moved through the heavens rather than observing them only when in some particularly favorable configuration. Modern telescopic observation indicates that when Brahe took particular care in determining the position of a fixed star his data were consistently accurate to 1′ of arc or better, a phenomenal achievement with the naked eye. His observations of planetary position seem normally to have been reliable to about 4′ of arc, more than twice the

accuracy achieved by the best observers of antiquity. But even more important than the accuracy of Brahe's individual observations was the reliability and the scope of the entire body of data he collected. In his own lifetime he and the observers he trained freed European astronomy from its dependence on ancient data and eliminated a whole series of apparent astronomical problems which had derived from bad data. His observations provided a new statement of the problem of the planets, and that new statement was a prerequisite to the problem's solution. No planetary theory could have reconciled the data employed by Copernicus.

Trustworthy, extensive, and up-to-date data are Brahe's primary contribution to the solution of the problem of the planets. But he has another and a larger rôle in the Copernican Revolution as the author of an astronomical system that rapidly replaced the Ptolemaic system as the rallying point for those proficient astronomers who, like Brahe himself, could not accept the earth's motion. Most of Brahe's reasons for rejecting Copernicus' proposal are the usual ones, though he developed them in more detail than most of his contemporaries. But Brahe gave particular emphasis to the immense waste space that the Copernican theory opened between the sphere of Saturn and the stars merely to account for the absence of observable parallactic motion. He himself had looked for parallax with his great new instruments. Since he found none, he felt forced to reject the earth's motion. The only alternative compatible with his observations would have required a distance between the stellar sphere and Saturn seven hundred times the distance between Saturn and the sun.

But Brahe was nothing if not a proficient astronomer. Though he rejected the earth's motion, he could not ignore the mathematical harmonies which the *De Revolutionibus* had introduced into astronomy. Those new harmonies did not convert him – they were not, for him, sufficiently strong evidence to counterbalance the difficulties inherent in the earth's motion – but they must at least have increased his discontent with the Ptolemaic system, and he rejected it, too, in favor of a third system of his own invention. Brahe's system, the "Tychonic," is shown in Figure 37. Once again the earth lies stationary at the geometric center of a stellar sphere whose daily rotation accounts for the diurnal circles of the stars. As in the Ptolemaic system, the sun, moon, and planets are carried westward daily with the stars by the outer sphere, and they have additional eastward orbital motions of their own. In the diagram these orbital motions are represented by circles, though in the full Tychonic system minor epicycles, eccentrics, and equants are also required. The circles of the moon and sun are centered on the earth; to this point the system is still Ptolemaic. But the centers of the five remaining planetary orbits are transferred from the center of the earth to the sun. Brahe's system is an extension, though perhaps not a conscious one, of Heraclides' system, which attributed sun-centered orbits to Mercury and Venus.

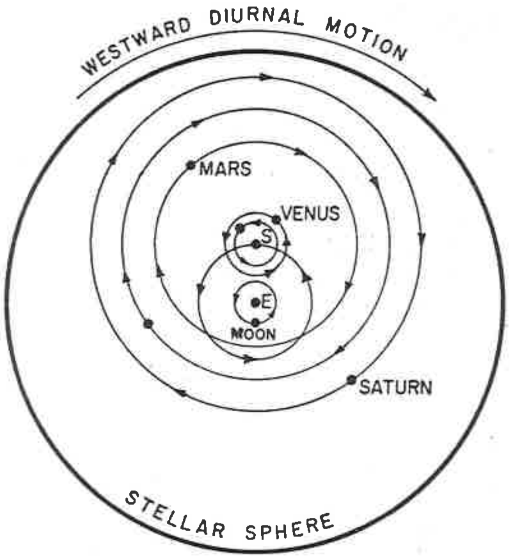


Figure 37. The Tychonic system. The earth is once again at the center of a rotating stellar sphere, and the moon and sun move in their old Ptolemaic orbits. The other planets are, however, fixed on epicycles whose common center is the sun.

The remarkable and historically significant feature of the Tychonic system is its adequacy as a compromise solution of the problems raised by the *De Revolutionibus*. Since the earth is stationary and at the center, all the main arguments against Copernicus' proposal vanish. Scripture, the laws of motion, and the absence of stellar parallax, all are reconciled by Brahe's proposal, and this reconciliation is effected without sacrificing any of Copernicus' major mathematical harmonies. The Tychonic system is, in fact, precisely equivalent mathematically to Copernicus' system. Distance determination, the apparent anomalies in the behavior of the inferior planets, these and the other new harmonies that convinced Copernicus of the earth's motion are all preserved.

The harmonies of the Tychonic system may be developed individually and in detail by the same techniques employed in discussing Copernicus' system, but for present purposes the following abbreviated demonstration of the mathematical equivalence of the Copernican and Tychonic systems should be sufficient. Imagine the sphere of the stars in Figure 37 immensely expanded until an observer on the moving sun could no longer observe any stellar parallax from opposite sides of the sun's orbit. This expansion does not affect the system's mathematical account of any of the planetary motions. Now imagine that within this expanded stellar sphere the various planets are driven about their orbits by a clockwork mechanism like that indicated schematically in Figure 38*a* for the earth, the sun, and Mars. In the diagram the sun is attached to the central earth by an arm of fixed length which carries it counterclockwise about the earth, and Mars is attached to the sun by another arm of fixed length which moves it counterclockwise about the moving sun. Since the lengths of both arms are fixed throughout the motion, the clockwork mechanism will produce just the circular orbits indicated in Figure 37.

Now imagine that, without interfering with the gears that drive the arms in Figure 38*a*, the whole mechanism is picked up and, with the arms turning as before, put down again with the sun fixed at the central position formerly held by the earth. This is the situation indicated in Figure 38*b*. The arms have the same lengths as before; they are driven at the same rates by the same mechanism; and they therefore retain the same *relative* positions at each instant of time. All of the geometric spatial relations of the earth, sun, and Mars in the diagram of Figure 38*a* are preserved by the arrangement of Figure 38*b*, and since only the fixed point of the mechanism has been changed, all the relative motions must be identical.

But the motions produced by the mechanism of Figure 38*b* are Copernican motions. That is, the fixed arms shown in the second diagram move both the earth and Mars in circular orbits about the sun, and those orbits are just the basic ones described by Copernicus. Carrying out the same argument with the hypothetical mechanism of Figure 38 elaborated to include all the planets, demonstrates that the equivalence is general. Omitting minor epicycles and eccentrics, which have no bearing on the harmonies of Copernicus' system, the Tychonic system is transformed to the Copernican system simply by holding the sun fixed instead of the earth. The relative motions of the planets are the same in both systems, and the harmonies are therefore preserved. Mathematically the only possible difference between the motions in the two systems is a parallactic motion of the stars, and that motion was eliminated at the start by expanding the stellar sphere until parallax was imperceptible.

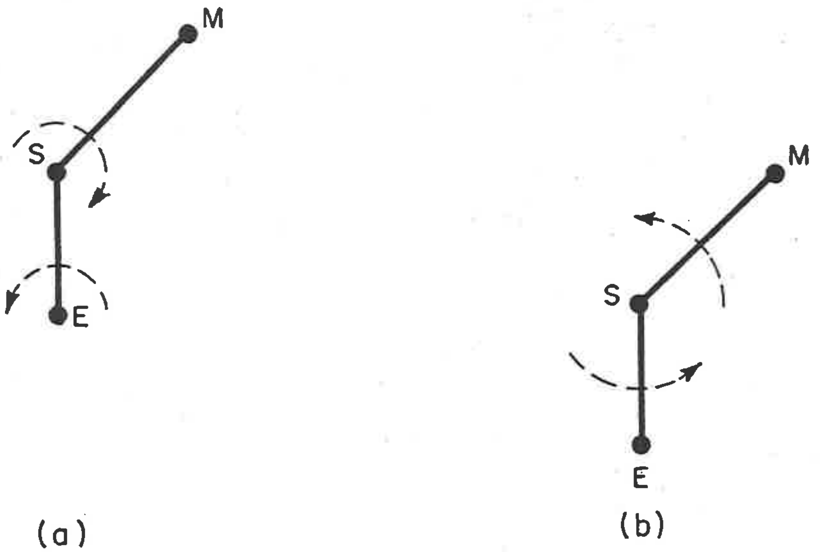


Figure 38. The geometrical equivalence of (*a*) the Tychonic and (*b*) the Copernican systems. In (*a*) the sun *S* is carried eastward about the stationary earth *E* by the the rigid arm *ES*. Simultaneously, the planet Mars, *M*, is carried westward about S by the steady rotation of the arm *SM*. Since *ES* rotates more rapidly than *SM*, the net motion of Mars is eastward except during the brief period when *SM* crosses over *ES*. In the second diagram (*b*) the same arms are shown rotating about the fixed sun S. The *relative positions* of *E*, *S*, and *M* are the same as those in (*a*), and they will stay the same while the arms in the two diagrams rotate. Notice particularly that in (*b*) the angle *ESM* must decrease as it does in (*a*) because *ES* rotates about the sun more rapidly than *SM*.

The Tychonic system has incongruities all its own: most of the planets are badly off center; the geometric center of the universe is no longer the center for most of the celestial motions; and it is difficult to imagine any physical mechanism that could produce planetary motions even approximately like Brahe's. Therefore the Tychonic system did not convert those few Neoplatonic astronomers, like Kepler, who had been attracted to Copernicus' system by its great symmetry. But it did convert most technically proficient non-Copernican astronomers of the day, because it provided an escape from a widely felt dilemma: it retained the mathematical advantages of Copernicus' system without the physical, cosmological, and theological drawbacks. That is the real importance of the Tychonic system. It was an almost perfect compromise, and in retrospect the system seems to owe its existence to the felt need for such a compromise. The Tychonic system, to which almost all the more erudite seventeenth-century Ptolemaic astronomers retreated, appears to be an immediate by-product of the *De Revolutionibus*.

Brahe himself would have denied this. He proclaimed that he had taken nothing in his system from Copernicus. But he can scarcely have been conscious of the pressures at work on him and his contemporaries. Certainly he knew both Ptolemaic and Copernican astronomy thoroughly before he thought of his own system, and he was clearly aware in advance of the predicament that his own system was to resolve. The immediate success of the system is one index of the strength and prevalence of the need. That two other astronomers disputed Brahe's priority and claimed to have worked out similar compromise solutions for themselves provides additional evidence for the role of the *De Revolutionibus* and the resulting climate of astronomical opinion in the genesis of the Tychonic system. Brahe and his system provide the first illustration of one of the major generalizations that closed the last chapter: the *De Revolutionibus* changed the state of astronomy by posing new problems for all astronomers.

Brahe's criticisms of Copernicus and his compromise solution of the problem of the planets show that, like most astronomers of his day, he was unable to break with traditional patterns of thought about the earth's motion. Among Copernicus' successors Brahe is one of the immense body of conservatives. But the effect of his work was not conservative. On the contrary, both his system and his observations forced his successors to repudiate important aspects of the Aristotelian-Ptolemaic universe and thus drove them gradually toward the Copernican camp. In the first place, Brahe's system helped to familiarize astronomers with the mathematical problems of Copernican astronomy, for geometrically the Tychonic and Copernican systems were identical. More important, Brahe's system, abetted by his observations of comets, to be discussed below, forced his followers to abandon the crystalline spheres which, in the past, had carried the planets about their orbits. In the Tychonic system, as indicated by Figure 37, the orbit of Mars intersects the orbit of the sun. Both Mars and the sun cannot, therefore, be embedded in spheres that carry them about, for the two spheres would have to penetrate and move through each other at all times. Similarly, the sun's sphere passes through the spheres of Mercury and Venus. Abandoning the crystalline spheres does not make a man a Copernican; Copernicus himself had utilized spheres to account for the planetary motions. But the spheres had, in one of a number of modifications, been an essential ingredient of the Aristotelian cosmological tradition which was the principal barrier to the success of Copernicanism. Any break with the tradition worked for the Copernicans, and the Tychonic system, for all its traditional elements, was an important break.

Brahe's skillful observations were even more important than his system in leading his contemporaries toward a new cosmology. They provided the essential basis for the work of Kepler, who converted Copernicus' innovation into the first really adequate solution of the problem of the planets. And even before they were used to revise Copernicus' system, the new data collected by Brahe suggested the necessity of another major departure from classical cosmology – they raised questions about the immutability of the heavens. Late in 1572, when Brahe was at the beginning of his career in astronomy, a new celestial body appeared in the constellation Cassiopeia, directly across the sky from the Big Dipper. When first observed it was very brilliant, as clear as Venus at its greatest brightness; during the next eighteen months the new occupant of the heavens grew gradually dimmer; and finally it vanished altogether early in 1574. From the start the new visitor drew the interest of scientists and nonscientists throughout Europe. It could not be a comet, the only sort of celestial apparition widely recognized by astronomers and astrologers, for it had no tail, and it always appeared in the same position against the sphere of the stars. Clearly it was a portent; astrological activity multiplied; and astronomers everywhere devoted their observations and their writings to the "new star" in the heavens.

The word "star" is the key to the astronomical and cosmological significance of the new phenomenon. If it were a star, then the immutable heavens had changed, and the basic contrast between the superlunary region and the corruptible earth was in question. If it were a star, the earth might more easily be conceived as a planet, for the transitory character of terrestrial affairs would now have been discovered in the heavens as well. Brahe and the best of his contemporaries did conclude that the visitor was a star. Observations like the one illustrated in Figure 39 indicated that it could not be located below the sphere of the moon or even close to the sublunary region. Probably it was among the stars, for it was observed to move with them. Another cause for cosmological upheaval had been discovered.

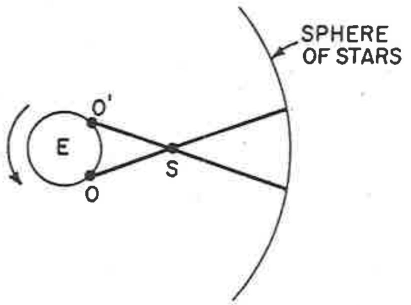


Figure 39. Diurnal parallax of a body below the stars. If S is between the earth and the sphere of the stars, then it should appear at different positions against the background of stars when observed by terrestrial observers at *O* and *O'*. Two observers are not required. The eastward rotation of the earth (or the equivalent westward rotation of the observed body and the stellar sphere) carries an observer from *O* to *O'* in six hours; as a result of the rotation the body S appears to change its position continually, returning to its starting point among the stars after twenty-four hours. If S were as close as the moon, its apparent displacement during six hours would be very nearly 1°. Bodies farther from the earth show less displacement.

With modern instruments the technique illustrated above is useful in determining the distances to the moon and planets, but naked-eye observations are not accurate enough for this application. The large size of the moon and its rapid orbital motion disguise the parallactic effect. The planets are too far away.

The sixteenth-century discovery of the mutability of the heavens might have been relatively ineffectual if the only evidence of superlunary change had been drawn from the new star, or nova, of 1572. It was a transient phenomenon; those who chose to reject Brahe's data could not be refuted; by the time the data were published the star had disappeared; and some less careful observers could always be discovered who had observed a parallax sufficient to place the nova below the moon. But fortunately additional and continuing evidence of superlunary change was provided by comets which Brahe observed carefully in 1577, 1580, 1585, 1590, 1593, and 1596. Once again no measurable parallax was observed, and the comets too were therefore located beyond the moon's sphere where they moved through the region formerly filled by the crystalline spheres.

Like the observations of the nova, Brahe's discussions of comets failed to convince all of his contemporaries. During the first decades of the seventeenth century Brahe was frequently attacked, occasionally with the same bitterness displayed toward Copernicus, by those who believed that other data proved comets and novas to be sublunary phenomena and that the inviolability of the heavens could therefore be preserved. But Brahe did convince a large number of astronomers of a basic flaw in the Aristotelian world view, and, more important, he provided a mode of argument by which skeptics could continuously check his conclusions. Comets bright enough to be seen with the naked eye appear every few years. After their superlunary character had been deduced from observation and then widely debated, the evidence that comets provided for the mutability of the heavens could not indefinitely be ignored or distorted. Once again the Copernicans were the gainers.

Somehow, in the century after Copernicus' death, all novelties of astronomical observation and theory, whether or not provided by Copernicans, turned themselves into evidence for the Copernican theory. That theory, we should say, was proving its fruitfulness. But, at least in the case of comets and novas, the proof is very strange, for the observations of comets and novas have nothing whatsoever to do with the earth's motion. They could have been made and interpreted by a Ptolemaic astronomer just as readily as by a Copernican. They are not, in any direct sense, by-products of the *De Revolutionibus*, as the Tychonic system was.

But neither can they be quite independent of the *De Revolutionibus* or at least of the climate of opinion within which it was created. Comets had been seen frequently before the last decades of the sixteenth century. New stars, though they appear less frequently to the naked eye than comets, must also have been occasionally accessible to observers before Brahe's time; one more appeared in the year before his death and a third in 1604. Even Brahe's fine instruments were not required to discover the superlunary character of novas and comets; a parallactic shift of 1° could have been measured without those instruments, and a number of Brahe's contemporaries did independently conclude that comets were superlunary using instruments that had been known for centuries. The Copernican Maestlin needed only a piece of thread to decide that the nova of 1572 was beyond the moon. In short, the observations with which Brahe and his contemporaries speeded the downfall of traditional cosmology and the rise of Copernicanism could have been made at any time since remote antiquity. The phenomena and the requisite instruments had been available for two millenniums before Brahe's birth, but the observations were not made or, if made, were not widely interpreted. During the last half of the sixteenth century age-old phenomena rapidly changed their meaning and significance. Those changes seem incomprehensible without reference to the new climate of scientific thought, one of whose first outstanding representatives is Copernicus. As suggested at the end of the last chapter, the *De Revolutionibus* marked a turning point, and there was to be no turning back.

Johannes Kepler

Brahe's work indicates that after 1543 even the opponents of Copernicanism, at least the ablest and most honest ones, could scarcely help promoting major reforms in astronomy and cosmology. Whether or not they agreed with Copernicus, he had changed their field. But the work of an anti-Copernican like Brahe does not show the extent of those changes. A better index of the novel problems that accrued to astronomy after Copernicus' death is provided by the research of Brahe's most famous colleague, Johannes Kepler (1571–1630). Kepler was a lifelong Copernican. He seems first to have been converted to the system by Maestlin when he was a student at the Protestant university of Tübingen, and his faith in it never wavered after his student days. Throughout his life he referred in the rhapsodic tones characteristic of Renaissance Neoplatonism to the suitability of the role that Copernicus had attributed to the sun. His first important book, the *Cosmographical Mystery*, published in 1596, opened with a lengthy defense of the Copernican system, emphasizing all those arguments from harmony that we discussed in Chapter 5 and adding many new ones besides: Copernicus' proposal explains why

Mars's epicycle had been so much larger than Jupiter's and Jupiter's than Saturn's; sun-centered astronomy shows why, of all the celestial wanderers, only the sun and moon fail to retrogress; and so on and on. Kepler's arguments are the same as Copernicus', though more numerous, but Kepler, in contrast to Copernicus, develops the arguments at length and with detailed diagrams. For the first time the full force of the mathematical arguments for the new astronomy was demonstrated.

But though Kepler was full of praise for the conception of a sun-centered planetary system, he was quite critical of the particular mathematical system that Copernicus had developed. Again and again Kepler's writings emphasized that Copernicus had never recognized his own riches and that after the first bold step, the transposition of the sun and earth, he had stayed too close to Ptolemy in developing the details of his system. Kepler was acutely and uncomfortably aware of the incongruous archaic residues in the *De Revolutionibus*, and he took it upon himself to eliminate them by exploiting fully the earth's new status as a planet governed, like the other planets, by the sun.

Copernicus had not quite succeeded in treating the earth as just another planet in a sun-centered system. Unlike the qualitative sketch in the First Book of the *De Revolutionibus*, the mathematical account of the planetary system developed in the later books attributed several special functions to the earth. For example, in the Ptolemaic system the planes of all planetary orbits had been constructed so that they intersected at the center of the earth, and Copernicus preserved this terrestrial function in a new form by drawing all orbital planes so that they intersected at the center of the earth's orbit. Kepler insisted that, since the sun governed the planets and the earth had no unique status, the planes of the orbits must intersect in the sun. By redesigning the Copernican system accordingly he made the first significant progress since Ptolemy in accounting for the north and south deviations of the planets from the ecliptic. Kepler had improved Copernicus' mathematical system by applying strict Copernicanism to it.

A similar insistence upon the parity of the planets enabled Kepler to eliminate a number of pseudo problems that had distorted Copernicus' work. Copernicus had, for example, believed that the eccentricities of Mercury and Venus were slowly changing, and he had added circles to his system to account for the variation. Kepler showed that the apparent change was due only to an inconsistency in Copernicus' definition of eccentricity. In the *De Revolutionibus* the eccentricity of the earth's orbit was measured from the sun (it is the distance SO_E in Figure 34*a*, p. 169) while the eccentricities of all other orbits were measured from the center of the earth's orbit (Mars's eccentricity is O_EO_M in Figure 34*b*). Kepler insisted that all planetary eccentricities must, in a Copernican universe, be computed in the same way and from the sun. When the new method was incorporated in his system, several of the apparent variations of eccentricity vanished, and the number of circles required in computation was reduced.

Each of these examples shows Kepler striving to adapt Copernicus' overly Ptolemaic mathematical techniques to the Copernican vision of a sun-dominated universe, and it was by continuing this effort that Kepler finally resolved the problem of the planets, transforming Copernicus' cumbersome system into a supremely simple and accurate technique for computing planetary position. His most essential discoveries were made while studying the motion of Mars, a planet whose eccentric orbit and proximity to the earth produce irregularities that had always challenged the ingenuity of mathematical astronomers. Ptolemy had been unable to account for its motion as satisfactorily as for that of the other planets, and Copernicus had not improved on Ptolemy. Brahe had attempted a new solution, undertaking a long series of observations specially for the purpose, but surrendering the problem as he encountered its full difficulties. Kepler, who had worked with Brahe during the last years of Brahe's life, inherited the new observations and, in the years after Brahe's death, took up the problem himself.

It was an immense labor which occupied much of Kepler's time for almost ten years. Two orbits had to be worked out: the orbit of Mars itself and the orbit of the earth from which Mars is observed. Again and again Kepler was forced to change the combination of circles used in computing these orbits. System after system was tried and rejected because it failed to conform to Brahe's brilliant observations. All of the intermediate solutions were better than the systems of Ptolemy and of Copernicus; some gave errors no larger than 8′ of arc, well within the limits of ancient observation. Most of the systems that Kepler discarded would have satisfied all earlier mathematical astronomers. But they had lived before Brahe, whose data were accurate to 4′ of arc. To us, Kepler said, Divine goodness has given a most diligent observer in Tycho Brahe, and it is therefore right that we should with a grateful mind make use of this gift to find the true celestial motions.

A long series of unsuccessful trials forced Kepler to conclude that no system based upon compounded circles would solve the problem. Some other geometric figure must, he thought, contain the key. He tried various sorts of ovals, but none eliminated the discrepancies between his tentative theory and observation. Then, by chance, he noticed that the discrepancies themselves varied in a familiar mathematical fashion, and investigating this regularity he discovered that theory and observation could be reconciled if the planets moved in elliptical orbits with variable speeds governed by a simple law which he also specified. These are the results that Kepler announced in *On the Motion of Mars*, first published at Prague in 1609. A mathematical technique simpler than any employed since Apollonius and Hipparchus yielded predictions far more accurate than any that had ever been made before. The problem of the planets had at last been solved, and it was solved in a Copernican universe.

The two laws that constitute Kepler's (and our) final solution of the problem of the planets are described in detail in Figure 40. The planets move in simple elliptical paths, and the sun occupies one of the two foci of each elliptical orbit – that is Kepler's First Law. His Second Law follows immediately, completing the description embodied in the First – the orbital speed of each planet varies in such a way that a line joining the planet to the sun sweeps through equal areas of the ellipse in equal intervals of time. When ellipses are substituted for the basic circular orbits common to Ptolemy's and Copernicus' astronomy and when the law of equal areas is substituted for the law of uniform motion about a point at or near the center, all need for eccentrics, epicycles, equants, and other *ad hoc* devices vanishes. For the first time a single uncompounded geometric curve and a single speed law are sufficient for predictions of planetary position, and for the first time the predictions are as accurate as the observations.

The Copernican astronomical system inherited by modern science is, therefore, a joint product of Kepler and Copernicus. Kepler's system of six ellipses made sun-centered astronomy work, displaying simultaneously the economy and the fruitfulness implicit in Copernicus' innovation. We must try to discover what was required for this transition of the Copernican system to its modern, Keplerian, form. Two of the prerequisites of Kepler's work are already apparent. He had to be a convinced Copernican, a man who would begin his search for more adequate orbits by treating the earth as a mere planet and who would construct the planes of all planetary orbits through the center of the sun. In addition, he needed Brahe's data. The data used by Copernicus and his European predecessors were too infected with errors to be

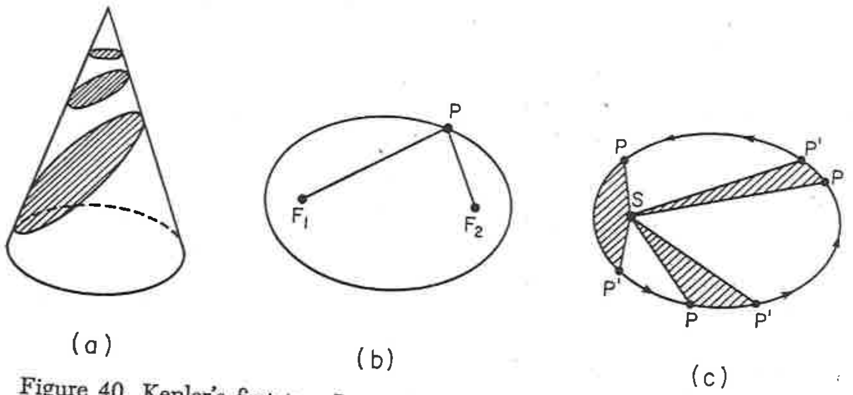


Figure 40. Kepler's first two Laws. Diagrams (*a*) and (*b*) define the ellipse, the geometric curve in which all planets that obey Kepler's First Law must move. In (*a*) the ellipse is shown as the closed curve in which a plane intersects a circular cone. When the plane is perpendicular to the axis of the cone, the intersection is a circle, a special case of the ellipse. As the plane is tilted, the curve of intersection is elongated into more typically elliptical patterns.

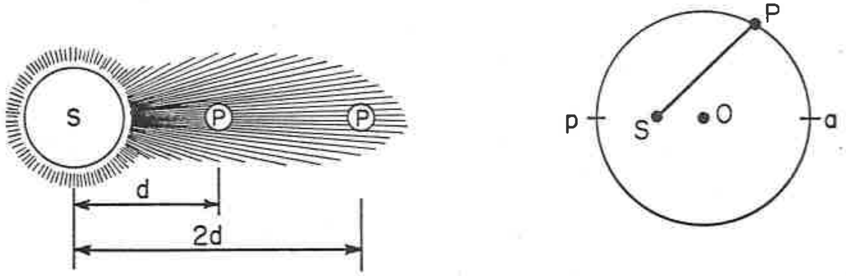
A more modern and somewhat more useful definition of the ellipse is given in diagram (*b*). If two ends of a slack string are attached to two points F_1 and F_2 in a plane, and if a pencil *P* is inserted into the slack and then moved so that it just keeps the string taut at all times, the point of the pencil will generate an ellipse. Changing the length of the string or moving the foci F_1 and F_2 together or apart alters the shape of the ellipse in the same way as a change in the tilt of the plane in diagram (*a*). Most planetary orbits are very nearly circular, and the foci of the corresponding ellipses are therefore quite close together.

Diagram (*c*) illustrates Kepler's Second Law, which governs orbital speed. The sun is at one focus of the ellipse, as required by the First Law, and its center is joined by straight lines to a number of planetary positions *P* and *P′*, arranged so that each of the three shaded sectors *SPP′* has the same area. The Second Law states that, since each of these areas is the same, the planet must move through each of the corresponding arcs *PP′* in equal times. When near the sun, the planet must move relatively quickly so that the short line *SP* will sweep out the same area per unit time as is swept out by the longer line *SP* when the planet is moving more slowly farther from the sun.

explained by any set of simple orbits, and even if freed from error they would not have sufficed. Observations less precise than Brahe's could have been explained, as Kepler himself showed, by a classical system of compounded circles. The process by which Kepler arrived at his famous Laws depends, however, upon more than the availability of accurate data and a prior commitment to the planetary earth. Kepler was an ardent Neoplatonist. He believed that mathematically simple laws are the basis of all natural phenomena and that the sun is the physical cause of all celestial motions. Both his most lasting and his most evanescent contributions to astronomy display these two aspects of his frequently mystical Neoplatonic faith.

In a passage quoted at the end of Chapter 4 Kepler described the sun as the body "who alone appears, by virtue of his dignity and power, suited . . . [to move the planets in their orbits], and worthy to become the home of God himself, not to say the first mover." This conviction, together with certain intrinsic incongruities discussed above, was his reason for rejecting the Tychonic system. It also played an immensely important role in his own research, particularly in his derivation of the Second Law upon which the First depends. In its origin the Second Law is independent of any but the crudest sort of observation. It arises rather from Kepler's physical intuition that the planets are pushed around their orbits by rays of a moving force, the *anima motrix*, which emanates from the sun. These rays must, Kepler believed, be restricted to the plane of the ecliptic, in or near which all the planets moved. Therefore the number of rays that impinged on a planet and the corresponding force that drove the planet around the sun would decrease as the distance between the planet and the sun increased. At twice the distance from the sun half as many rays of the *anima motrix* would fall on a planet (Figure 41*a*), and the velocity of the planet in its orbit would, in consequence, be half of its orbital velocity at its original distance from the sun. A planet, *P*, moving about the sun, S, on an eccentric circle (Figure 41*b*) or some other closed curve must move at a speed inversely proportional to *SP*. The speed will be greatest when the planet is at the perihelion, *p*, closest to the sun, and least at the aphelion, *a*, where the planet is farthest from the sun. As the planet moves around the orbit, its speed will vary continually between these extremes.

Long before he began to work on elliptical orbits or stated the law of areas in its familiar modern form, Kepler had worked out this inverse-distance speed law to replace both the ancient law of uniform circular motion and the Ptolemaic variant which permitted uniform motion with respect to an equant point. This early speed law was very much "pulled from a hat" by a strange intuition – one that was rapidly discarded by his successors – of the forces that must govern a sun-dominated universe. Furthermore, this early form is not quite correct. The later law of areas, Kepler's so-called Second Law, is not quite equivalent to the inverse-distance law, and the law of areas gives somewhat better results. But when used to compute planetary position the two forms of the speed law lead to almost the same predictions. Kepler mistakenly thought the two equivalent in principle and used them interchangeably throughout his life. For all its visionary overtones the early Neoplatonic speed law proved fundamental in Kepler's most fruitful research.



(a) (b)

Figure 41. Kepler's earliest speed law. Diagram (*a*), which shows typical rays of the *anima motrix* radiating from the sun, illustrates the physical theory from which Kepler derived the law. Diagram (*b*) shows how the law could be applied to a planet moving on an eccentric circle.

Unlike his derivation of the speed law, Kepler's work on elliptical orbits was completely dependent upon the most painstaking and exhaustive study of the best available astronomical observations. Trial orbit after trial orbit had to be abandoned because, after laborious computation, it did not quite match Brahe's data. Kepler's scrupulous attempt to fit his orbits to objective data is often cited as an early example of the scientific method at its best. Yet even the law of elliptical orbits, Kepler's First Law, was not derived from observation and computation alone. Unless the planetary orbits are assumed to be precisely reëntrant (as they were after Kepler's work but not before), a speed law is required to compute orbital shape from naked-eye data. When analyzing Brahe's observations, Kepler made constant use of his earlier Neoplatonic guess.

The interrelation of orbit, speed law, and observation was obscured in our earlier discussions of astronomical theory, because ancient and medieval astronomers chose a simple speed law in advance. Before Kepler astronomers assumed that each of the compounded circles which moved a planet around its orbit must rotate uniformly with respect to a point at or near its center. Without some such assumption they could not have begun the elaboration of orbits to fit observations, for in the absence of a speed law the specification of an orbit tells little or nothing about where a planet will appear among the stars at a particular time. Neither speed law nor orbit can be independently derived from or checked against observation. Therefore, when Kepler rejected the ancient law of uniform motion, he had to replace it or else abandon planetary computations entirely. In fact, he rejected the ancient law only after (and probably because) he had developed a law of his own – a law that his Neoplatonic intuition told him was better suited than its ancient counterpart to govern celestial motions in a sun-dominated universe.

Kepler's derivation of the inverse-distance law displays his belief in mathematical harmonies as well as his faith in the causal role of the sun. Having developed the conception of the *anima motrix* Kepler insisted that it must operate in the simplest way compatible with crude observation. He knew, for example, that planets move fastest at perihelion, but he had few other data, none of them quantitative, on which to base an inverse-distance law. But Kepler's belief in number harmonies and the role of this belief in his work is more forcefully exhibited in another one of the laws that modern astronomy inherits from him. This is Kepler's so-called Third Law, announced during 1619 in the *Harmonies of the World.*

The Third Law was a new sort of astronomical law. Like their ancient and medieval counterparts the First and Second Laws govern only the motions of individual planets in their individual orbits. The Third Law, in contrast, established a relation between the speeds of planets in different orbits. It states that if T_1 and T_2 are the periods that two planets require to complete their respective orbits once, and if R_1 and R_2 are the average distances between the corresponding planets and the sun, then the ratio of the squares of the orbital periods is equal to the ratio of the cubes of the average distances from the sun, or $(T_1 / T_2)^2 = (R_1 / R_2)^3$. This is a fascinating law, for it points to a regularity never before perceived in the planetary system. But, at least in Kepler's day, that was all it did. The Third Law did not, in itself, change the theory of the planets, and it did not permit astronomers to compute any quantities that were previously unknown. The sizes and the periods associated with each planetary orbit were available in advance.

But though it had little immediate practical use, the Third Law is just the sort of law that most fascinated Kepler throughout his career. He was a mathematical Neoplatonist or Neopythagorean who believed that all of nature exemplified simple mathematical regularities which it was the scientists' task to discover. To Kepler and others of his turn of mind a simple mathematical regularity was itself an explanation. To him the Third Law in and of itself explained why the planetary orbits had been laid out by God in the particular way that they had, and that sort of explanation, derived from mathematical harmony, is what Kepler continually sought in the heavens. He propounded a number of other laws of the same kind, laws which we have since abandoned because, though harmonious, they do not fit observation well enough to seem significant. But Kepler was not so selective. He thought that he had discovered and demonstrated a large number of these mathematical regularities, and they were his favorite astronomical laws.

In Kepler's first major work, the *Cosmographical Mystery,* he argued that both the number of the planets and the size of their orbits could be understood in terms of the relation between the planetary spheres and the five regular or "cosmic" solids. These are the solids shown in Figure 42*a*, and they have the unique characteristic that all of the faces of each solid are identical and that only equilateral figures are used for faces. It had been shown in antiquity that there could be only five such solids: cube, tetrahedron, dodecahedron, icosahedron, and octahedron. Kepler proclaimed that if the sphere of Saturn were circumscribed about the cube within which Jupiter's sphere was inscribed, and if the tetrahedron were placed just inside Jupiter's sphere with Mars's sphere inscribed in it, and so on for the three other solids and three other spheres, then the relative dimensions of all the spheres would be just those that Copernicus had determined by measurement. The construction is shown in Figure 42*b*. If it is to be used, there can be only six planets, corresponding to the five regular solids, and when it is used the permissible relative dimensions of the planetary spheres are determined. That, said Kepler, is why there are only six planets and why they are arranged as they are. God's nature is mathematical.

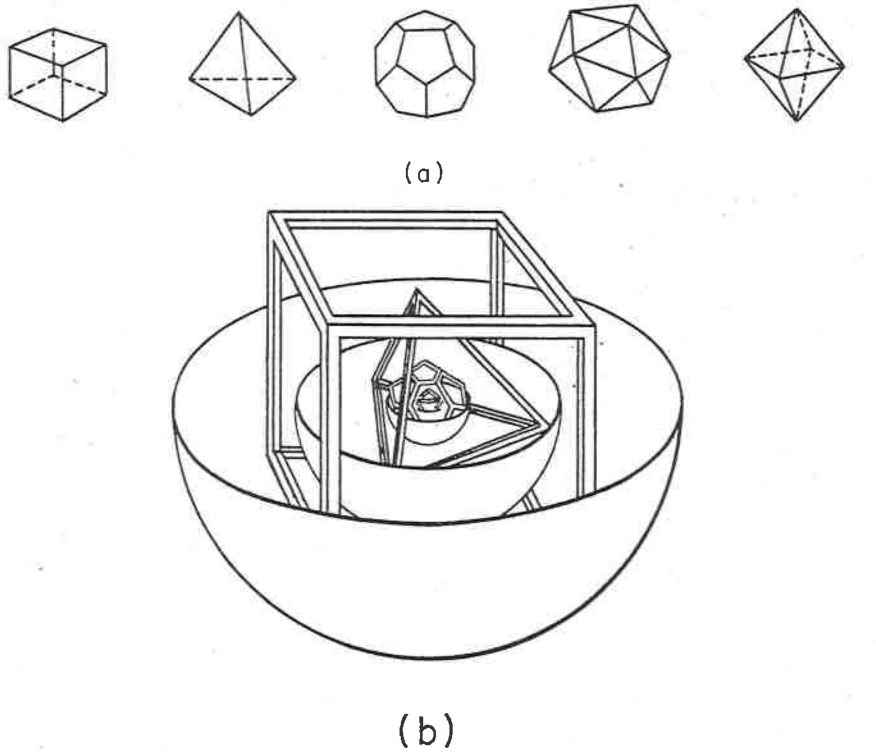


Figure 42. Kepler's application of the five regular solids. Diagram (*a*) shows the solids themselves. From left to right they are: cube, tetrahedron, dodecahedron, icosahedron, and octahedron. Their order is the one that Kepler developed to account for the sizes of the planetary spheres. Diagram (*b*) shows the solids in this application. Saturn's sphere is circumscribed about the cube, and Jupiter's sphere is inscribed in it. The tetrahedron is inscribed in Jupiter's sphere, and so on.

Kepler's use of the regular solids was not simply a youthful extravagance, or if it was, he never grew up. A modified form of the same law appeared twenty years later in his *Harmonies of the World*, the same book that propounded the Third Law. Also in that book Kepler elaborated a new set of Neoplatonic regularities which related the maximum and minimum orbital speeds of the planets to the concordant intervals of the musical scale. Today this intense faith in number harmonies seems strange, but that is at least partly because today scientists are prepared to find their harmonies more abstruse. Kepler's application of the faith in harmonies may seem naïve, but the faith itself is not essentially different from that motivating bits of the best contemporary research. Certainly the scientific attitude demonstrated in those of Kepler's "laws" which we have now discarded is not distinguishable from the attitude which drove him to the three Laws that we now retain. Both sets, the "laws" and the Laws, arise from the same renewed faith in the existence of mathematical harmony that had so large a role in driving Copernicus to break with the astronomical tradition and in persuading him that the earth was, indeed, in motion. But in Kepler's work, and particularly in the parts of it that we have now discarded, the Neoplatonic drive to discover the hidden mathematical harmonies embedded in nature by the Divine Spirit are illustrated in a purer and more distinct form.

Galileo Galilei

Kepler solved the problem of the planets. Ultimately his version of Copernicus' proposal would almost certainly have converted all astronomers to Copernicanism, particularly after 1627 when Kepler issued the *Rudolphine Tables*, derived from his new theory and clearly superior to all the astronomical tables in use before. The story of the astronomical components of the Copernican Revolution might therefore end with the gradual acceptance of Kepler's work because that work contains all the elements required to make the Revolution in astronomy endure. But, in fact, the astronomical components of the story do not end there. In 1609 the Italian scientist Galileo Galilei (1564–1642) viewed the heavens through a telescope for the first time, and as a result contributed to astronomy the first qualitatively new sort of data that it had acquired since antiquity. Galileo's telescope changed the terms of the riddle that the heavens presented to astronomers, and it made the riddle vastly easier to solve, for in Galileo's hands the telescope disclosed countless evidences for Copernicanism. But Galileo's new statement of the riddle was not formulated until after the riddle had been solved by other means. If it had been announced earlier, the story of the Copernican Revolution would be quite different. Coming when it did, Galileo's astronomical work contributed primarily to a mopping-up operation, conducted after the victory was clearly in sight.

In 1609 the telescope was a new instrument, though it is not clear just how new it was. Galileo heard that some Dutch lens grinder had combined two lenses in a way that magnified distant objects; he tried various combinations himself and quickly produced a low-power telescope of his own. Then he did something which, apparently, no one had done before: he directed his glass to the heavens, and the result was astounding. Every observation disclosed new and unsuspected objects in the sky. Even when the telescope was directed to familiar celestial objects, the sun, moon, and planets, remarkable new aspects of these old friends were discovered. Galileo, who had been a Copernican for some years before he knew of the telescope, managed to turn each new discovery into an argument for Copernicanism.

The telescope's first disclosure was the new worlds in the firmament about which Donne, only two years later, complained. Wherever he turned his glass, Galileo found new stars. The population of the most crowded constellations increased. The Milky Way, which to the naked eye is just a pale glow in the sky (it had frequently been explained as a sublunary phenomenon, like comets, or as a reflection of diffused light from the sun and moon) was now discovered to be a gigantic collection of stars, too dim and too little separated to be resolved by the naked eye. Overnight the heavens were crowded by countless new residents. The vast expansion of the universe, perhaps its infinitude, postulated by some of the Copernicans, seemed suddenly less unreasonable. Bruno's mystical vision of a universe whose infinite extent and population proclaimed the infinite procreativeness of the Deity was very nearly transformed into a sense datum.

Observation of the stars also resolved a more technical difficulty that had confronted the Copernicans. Naked-eye observers had estimated the angular diameter of stars and, with the aid of the accepted figure for the distance between the earth and the sphere of the stars, had transformed the angular diameter into an estimate of linear dimensions. In a Ptolemaic universe these estimates had given not

unreasonable results: the stars might be as large as the sun, or thereabouts. But, as Brahe repeatedly emphasized in his attacks upon Copernicanism, if the Copernican universe were as large as the absence of stellar parallax demanded, then the stars must be incredibly large. The brighter stars of the heavens must, Brahe computed, be so large that they would more than fill the entire orbit of the earth, and this he not unnaturally refused to believe. But when the telescope was directed to the heavens, Brahe's problem turned out to be an apparent problem only. The stars did not need to be so large as he had estimated. Though the telescope immensely increased the number of stars visible in the skies, it did not increase their apparent size. Unlike the sun, moon, and planets, all of which were magnified by Galileo's glass, the stars retained the size they had had before. It became apparent that the angular diameter of stars had been immensely overestimated by naked-eye observation, an error now explained as a consequence of atmospheric turbulence which blurs the images of stars and spreads them over a wider area in the eye than would be covered by their undistorted image alone. The same effect makes the stars seem to twinkle; it is largely suppressed by the telescope, which gathers a larger number of rays to the eye.

The stars did not, however, provide the only, or even the best, evidence for Copernicanism. When Galileo turned his telescope to the moon, he found that its surface was covered by pits and craters, valleys and mountains. Measuring the length of the shadows cast into craters and by mountains at a time when the relative positions of the sun, moon, and earth were known, he was able to estimate the depths of the moon's declivities and the height of its protuberances and to begin a three-dimensional description of the moon's topography. It was not, Galileo decided, very different from the earth's topography. Therefore, like the measurements of the parallax of comets, telescopic observations of the moon raised doubts about the traditional distinction between the terrestrial and the celestial regions, and those doubts were reinforced almost immediately by telescopic observations of the sun. It too showed imperfections, dark spots which appeared and disappeared on its surface. The very existence of the spots conflicted with the perfection of the celestial region; their appearance and disappearance conflicted with the immutability of the heavens; and, worst of all, the motion of the spots across the sun's disk indicated that the sun rotated continually on its axis and thus provided a visible paradigm for the axial rotation of the earth.

But this was not the worst. Galileo looked at Jupiter with his telescope and discovered four small points of light quite close to it in the sky. Observations made on successive nights showed that they continually rearranged their relative positions in a manner that could most simply be explained by supposing that they revolved continually and quite rapidly about Jupiter (Figure 43). These bodies were the four principal moons of Jupiter, and their discovery had an immense impact upon the seventeenth-century imagination. There were, it appeared, new worlds "in the Planets" as well as in "the Firmament." More important, these new worlds could not be conceived, on either the Ptolemaic or the Copernican hypothesis, to move in roughly circular orbits about the center of the universe. Apparently they moved around a planet, and their behavior was therefore the same as that of the earth's moon in Copernican astronomy. The discovery of Jupiter's moons therefore reduced the force of one more objection to the Copernican system. The old astronomy, as well as the new, would have to admit the existence of satellites, governed by planets. In addition, and perhaps most consequential of all, the observations of Jupiter provided a visible model of the Copernican solar system itself. Here in planetary space was a heavenly body surrounded by its own "planets," just as the planets previously known encircled the sun. The arguments for Copernicanism were multiplied by the telescope almost as rapidly as the heavenly bodies themselves.

Figure 43. Three successive observations of Jupiter and its satellites separated by intervals of several days. The constant rearrangement of the four small satellites is most easily explained by supposing that the satellites are constantly rotating about the larger planet.

Many other arguments were derived from telescopic observation, but only the observations of Venus provide sufficiently direct evidence for Copernicus' proposal to concern us here. Copernicus himself had noted in Chapter 10 of the First Book of the *De Revolutionibus* that the appearance of Venus could, if observable in detail, provide direct information about the shape of Venus's orbit. If Venus is attached to an epicycle moving on an earth-centered deferent, and if the center of the epicycle is always aligned with the sun, then, as indicated by Figure 44*a*, an observer on the earth should never be able to see more than a crescent edge of the planet. But if Venus's orbit encircles the sun as in Figure 44*b*, then an earthbound observer should be able to see an almost complete cycle of phases, like the moon's; only phases near "new" and "full" would be imperceptible, because Venus would then be too close to the sun. Venus's phases can not be distinguished with the naked eye, which sees the planets as mere shapeless points. But the telescope enlarges planets sufficiently to give them shape,

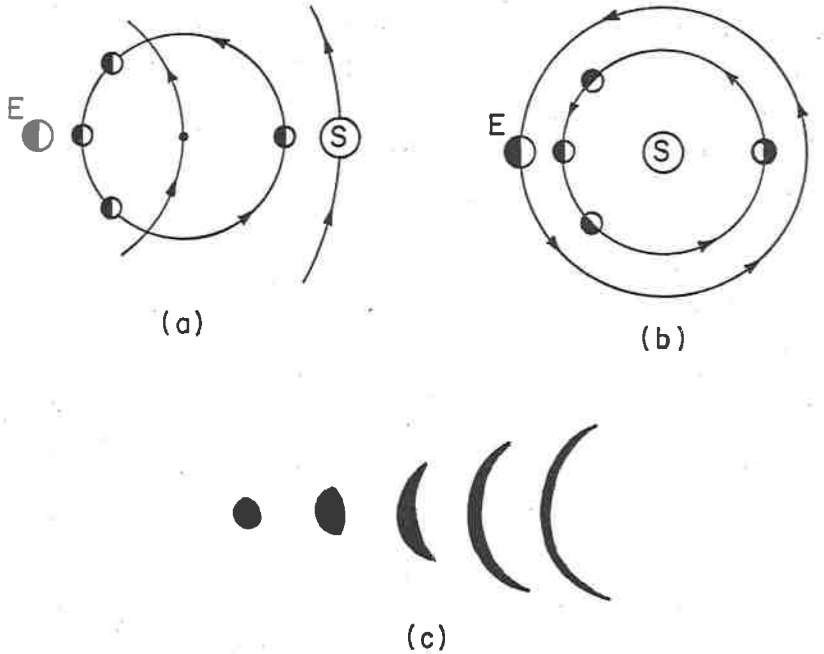


Figure 44. The phases of Venus in (*a*) the Ptolemaic system, (*b*) the Copernican system, and (*c*) as observed with a low-power telescope. In (*a*) an observer on the earth should never see more than a thin crescent of the lighted face. In (*b*) he should see almost the whole face of Venus illuminated just before or after Venus crosses behind the sun. This almost circular silhouette of Venus when it first becomes visible as an evening star is drawn from observations with a low-power telescope on the left of diagram (*c*). The successive observations drawn on the right show how Venus wanes and simultaneously increases in size as its orbital motion brings it closer to the earth.

and, as indicated in Figure 44c, its shape provides strong evidence that Venus moves in a sun-centered orbit.

The evidence for Copernicanism provided by Galileo's telescope is forceful, but it is also strange. None of the observations discussed above, except perhaps the last, provides direct evidence for the main tenets of Copernicus' theory – the central position of the sun or the motion of the planets about it. Either the Ptolemaic or the Tychonic universe contains enough space for the newly discovered stars; either can be modified to allow for imperfections in the heavens and for satellites attached to celestial bodies; the Tychonic system, at least, provides as good an explanation as the Copernican for the observed phases of and distance to Venus. Therefore, the telescope did not prove the validity of Copernicus' conceptual scheme. But it did provide an immensely effective weapon for the battle. It was not proof, but it was propaganda.

After 1609 the main psychological force of the Ptolemaic system was its conservatism. Those who held to it would not be forced to learn new ways. But if the Ptolemaic system required extensive revisions to adjust it to the results of telescopic observation, it would lose even its conservative appeal. It was very nearly as easy to make the full transition to Copernicanism as to adjust to the requisite new version of Ptolemy, and many of those who took the observations seriously did make the full transition. These new converts may also have been impelled by another consideration: the Copernicans, or at least the cosmologically more radical ones, had anticipated the sort of universe that the telescope was disclosing. They had predicted a detail, the phases of Venus, with precision. More important, they had anticipated, at least vaguely, the imperfections and the vastly increased population of the heavens. Their vision of the universe showed marked parallels to the universe that the telescope made manifest. There are few phrases more annoying or more effective than "I told you so."

For the astronomically initiate the evidence of the telescope was, perhaps, superfluous. Kepler's Laws and his *Rudolphine Tables* would have been equally, though far more slowly, effective. But it is not on the astronomically initiate that the telescope had the greatest immediate impact. The first unique role of the telescope was providing generally accessible and nonmathematical documentation for the Copernican point of view. After 1609 men who knew only a smattering of astronomy could look through a telescope and see for themselves that the universe did not conform to the naïve precepts of common sense, and during the seventeenth century they did look. The telescope became a popular toy. Men who had never before shown interest in astronomy or in any science bought or borrowed the new instrument and eagerly scanned the heavens on clear nights. The amateur observer became a well-known figure, a subject for both emulation and parody. With him came a new literature. The beginnings of both popular science and science fiction are to be discovered in the seventeenth century, and at the start the telescope and its discoveries were the most prominent subjects. That is the greatest importance of Galileo's astronomical work: it popularized astronomy, and the astronomy that it popularized was Copernican.

The Decline of Ptolemaic Astronomy

Kepler's ellipses and Galileo's telescope did not immediately crush the opposition to Copernicanism. On the contrary, as we noted at the start of this chapter, the bitterest and most vociferous opposition was not organized until after both Kepler and Galileo had made their principal astronomical discoveries. Kepler's work, like Copernicus' sixty-five years earlier, was accessible only to trained astronomers, and, in spite of the great accuracy that Kepler was known to have achieved, many astronomers found his noncircular orbits and his new techniques for determining planetary velocities too strange and uncongenial for immediate acceptance. Until after the middle of the century a number of eminent European astronomers can be found trying to show that Kepler's accuracy can be duplicated with mathematically less radical systems. One tried to revert to epicycles; another consented to ellipses but insisted that the speed of a planet was uniform with respect to the unoccupied focus of the ellipse; still others tried orbits of another shape. None of these attempts was successful, and as the century continued fewer and fewer of them were made. But not until the last decades of the seventeenth century did Kepler's Laws become the universally accepted basis for planetary computations even among the best practicing European astronomers.

Galileo's observations met initially even greater opposition, though from a different group. With the advent of the telescope Copernicanism ceased to be esoteric. It was no longer primarily the concern of highly trained mathematical astronomers. Therefore it became more disquieting and, to some, more dangerous. The new worlds discovered by the telescope were a primary source of Donne's malaise. A few years later telescopic observations provided part of the impetus necessary to set in motion the ecclesiastical machinery of official Catholic opposition to Copernicanism. After Galileo had announced his observations in 1610, Copernicanism could not be dismissed as a mere mathematical device, useful but without physical import. Nor could even the most optimistic still regard the concept of the earth's motion as a temporary lunacy likely to vanish naturally if left to itself. The telescopic discoveries therefore provided a natural and appropriate focus for much of the continuing opposition to Copernicus' proposal. They showed the real cosmological issues at stake more quickly and more clearly than pages of mathematics.

The opposition took varied forms. A few of Galileo's more fanatical opponents refused even to look through the new instrument, asserting that if God had meant man to use such a contrivance in acquiring knowledge, He would have endowed men with telescopic eyes. Others looked willingly or even eagerly, acknowledged the new phenomena, but claimed that the new objects were not in the sky at all; they were apparitions caused by the telescope itself. Most of Galileo's opponents behaved more rationally. Like Bellarmine, they agreed that the phenomena were in the sky but denied that they proved Galileo's contentions. In this, of course, they were quite right. Though the telescope argued much, it proved nothing.

The continuing opposition to the results of telescopic observation is symptomatic of the deeper-seated and longer-lasting opposition to Copernicanism during the seventeenth century. Both derived from the same source, a subconscious reluctance to assent in the destruction of a cosmology that for centuries had been the basis of everyday practical and spiritual life. The conceptual reorientation that, after Kepler and Galileo, meant economy to scientists frequently meant a loss of conceptual coherence to men like Donne and Milton whose primary concerns were in other fields, and some men whose first interests were religious, moral, or aesthetic continued to oppose Copernicanism bitterly for a very long time. The attacks were scarcely abated by the middle of the seventeenth century. Many important tracts insisting on a literal interpretation of Scripture and upon the absurdity of the earth's motion continued to appear during the first decades of the eighteenth century. As late as 1873 the ex-president of an American Lutheran teachers' seminary published a work condemning Copernicus, Newton, and a distinguished series of subsequent astronomers for their divergence from scriptural cosmology. Even today the newspapers occasionally report the dicta of a dotard who insists upon the uniqueness and stability of the earth. Old conceptual schemes never die!

But old conceptual schemes do fade away, and the gradual extinction of the concept of the earth's uniqueness and stability clearly, if almost imperceptibly, dates from the work of Kepler and Galileo. During the century and a half following Galileo's death in 1642, a belief in the earth-centered universe was gradually transformed from an essential sign of sanity to an index, first, of inflexible conservatism, then of excessive parochialism, and finally of complete fanaticism. By the middle of the seventeenth century it is difficult to find an important astronomer who is not Copernican; by the end of the century it is impossible. Elementary astronomy responded more slowly, but during the closing decades of the century Copernican, Ptolemaic, and Tychonic astronomy were taught side by side in many prominent Protestant universities, and during the eighteenth century lectures on the last two systems were gradually dropped. Popular cosmology felt the impact of Copernicanism most slowly of all; most of the eighteenth century was required to endow the populace and its teachers with a new common sense and to make the Copernican universe the common property of Western man. The triumph of Copernicanism was a gradual process, and its rate varied greatly with social status, professional affiliation, and religious belief. But for all its difficulties and vagaries it was an inevitable process. At least it was as inevitable as any process known to the historian of ideas.

The Copernican universe assimilated during the century and a half after Galileo's death was not, however, the universe of Copernicus or even of Galileo and Kepler. Nor was its novel structure derived predominantly from astronomical evidence. Copernicus and the astronomers who followed him made the first successful substantive break with Aristotelian cosmology, and they began the construction of the new universe. But the early Copernicans did not fully see where their work was leading. During the seventeenth century many other scientific and cosmological currents converged to modify and complete the cosmological framework that had directed their thought. The Copernicanism that the eighteenth, nineteenth, and twentieth centuries inherited is a Copernicanism rebuilt to suit the seventeenth-century conception of a Newtonian world machine. That final historic integration of Copernican astronomy into the complete and coherent universe envisaged by the seventeenth century is the subject of our final chapter, though we shall treat it only with the limited detail and foreshortened perspective appropriate to an epilogue. In so far as the Copernican Revolution was a revolution merely in astronomical thought, its story ends here. What follows is a partial sketch of the larger revolution in science and cosmology — a revolution which began with Copernicus and through which the Copernican Revolution was at last completed.

7

THE NEW UNIVERSE

The New Scientific Perspective

Kepler and Galileo compiled impressive evidence for the earth's status as a moving planet. The concept of elliptical orbits and the new data collected with telescopes were, however, only *astronomical* evidence *for* the planetary earth. They did not answer the *non-astronomical* evidence *against* it. While they remained unanswered, each of those arguments, whether physical, or cosmological, or religious, testified to an immense disparity between the concepts of technical astronomy and those employed in other sciences and in philosophy. The more difficult it became to doubt the astronomical innovation, the more urgent was the need for adjustments in other fields of thought. Until those adjustments were made, the Copernican Revolution was incomplete.

Most large-scale upheavals in scientific thought produce similar conceptual disparities. We are today, for example, in the late stages of a scientific revolution initiated by Planck, Einstein, and Bohr. Their new concepts and others upon which the contemporary revolution depends show close historical parallels to Copernicus' concept of a planetary earth. Conceptions like Bohr's atom and Einstein's finite but unbounded space were introduced to solve pressing problems in a single scientific specialty. Those who accepted them did so initially because of the immense felt need in the field of their origin and in spite of their obvious conflict with common sense, physical intuition, and the basic concepts of other sciences. For a time they were used by the specialist even though, within the larger climate of scientific thought, they seemed incredible.

Continued use, however, makes even the strangest conception plausible, and once plausible the new conception gains a larger scientific function. It ceases, in the vocabulary of Chapter 1, to be merely a paradoxical and *ad hoc* device for economically describing the